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SESSIONS I.

Applied Artificial Intelligence

Comparative Analysis of Lightweight CNNs for Multilingual Handwritten Character Recognition

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Abstract— Handwritten character recognition remains a fundamental problem in pattern recognition, with applications ranging from digital document processing to historical manuscript digitization. Multilingual handwritten character recognition introduces additional challenges due to variations in scripts, diacritics, and handwriting styles. In this work, we explore lightweight convolutional neural networks (CNNs) for recognizing handwritten characters across multiple languages using the merged T-H-E dataset, which combines visually identical upper- and lower-case characters into 54 classes. Four CNN architectures, as LeNet-5 (baseline), Simple CNN, Depthwise-CNN, and MiniVGGNet, are evaluated based on their efficiency, number of parameters, training time, and misclassification behavior. Experiments were conducted under standardized hyperparameters and using a fixed random seed to ensure a fair comparison. Our analysis shows that lightweight networks can achieve competitive performance while requiring minimal computational resources, and the study provides insights into common misclassification patterns related to visually similar characters and diacritics. These findings establish a fast and resource-efficient baseline for multilingual handwritten character recognition on small binary datasets.

Keywords—*deep learning, handwritten character recognition, convolutional neural network, lightweight CNNs*

I. INTRODUCTION

Handwritten character recognition (HCR) is a core problem in document analysis and pattern recognition. Automated recognition of handwritten characters enables applications such as digital document processing, historical manuscript digitization, postal sorting, and educational tools. While recognition of digits and single-language alphabets has been extensively studied, multilingual HCR introduces additional challenges due to variations in scripts, handwriting styles, and diacritics.

Deep learning, a subfield of machine learning, involves multilayered neural networks that can learn complex patterns in large datasets. This enables the development of artificial intelligence systems that surpass human performance in tasks such as image and document recognition [1].

Deep learning, and in particular convolutional neural networks (CNNs), was introduced in 1998 by French researcher Yann LeCun as an extension of the neocognitron model [2] and have become the standard approach for HCR. Classical architectures such as LeNet-5 [3] have demonstrated strong performance on MNIST [4], and extensions such as EMNIST [5] provide large-scale benchmarks for handwritten

letters. Lightweight CNNs have shown that small networks can achieve competitive accuracy with significantly fewer parameters [6], [7]. For multilingual datasets, efficient models are particularly valuable because large pretrained networks often fail on small binary datasets, as confirmed in experiments with MobileNet on the T-H-E dataset [8].

Multilingual datasets, such as T-H-E, extend this concept by including multiple alphabets and special characters, providing a benchmark for evaluating models on English, Hungarian, and Turkish scripts. The merged version of T-H-E reduces ambiguity by combining visually identical upper- and lower-case characters, resulting in 54 classes.

In this study, we evaluate four CNN architectures on the merged T-H-E dataset: LeNet-5 (baseline), Simple CNN, Depthwise-CNN, and MiniVGGNet. All models were trained using a fixed random seed and early stopping to ensure reproducibility and fair comparison. We analyze not only accuracy but also training efficiency, parameter requirements, and patterns of misclassification among visually similar letters and diacritics. By comparing these architectures, we aim to identify accurate, fast, and resource-efficient networks suitable for multilingual handwritten character recognition in low-resource settings.

II. RELATED WORKS

Handwritten character recognition (HCR) has been extensively studied, particularly for Latin scripts. Early approaches relied on feature extraction combined with classical classifiers such as k-nearest neighbors or support vector machines [9], [10]. With the advent of deep learning, convolutional neural networks (CNNs) became the dominant method, starting with LeNet-5, which achieved state-of-the-art results on MNIST [3], [4]. Subsequent works extended CNNs to larger and more complex datasets, including EMNIST, which includes both letters and digits [5]. EMNIST offers multiple splits such as ByClass, ByMerge, Letters, and Balanced, providing a range of challenges for character recognition systems.

Other MNIST-like character datasets include KMNIST (Kuzushiji-MNIST), which consists of 28×28 grayscale images of classical Japanese cursive characters [11]. These datasets provide benchmarks for evaluating CNNs on non-Latin scripts and demonstrate the importance of handling diverse character shapes and writing styles. The T-H-E dataset [8] expands this concept by providing a multilingual dataset with 54 classes, merging visually identical upper- and lower-

case characters, thus reducing misclassification and class imbalance.

A deep learning model using convolutional neural networks (CNNs) for multilingual handwritten character recognition covering English, Hindi, and Bengali scripts achieved 92.47% accuracy, outperforming individual single-language models [12]. This recent study emphasized tuning hyperparameters and activation functions to improve performance and demonstrated its effectiveness on multiple publicly available datasets.

Offered a model for multilingual character recognition, introducing a robust convolutional recurrent neural network (CRNN) model to accommodate the vagaries of both Tamil and English handwritten character recognition [13]. The proposed CRNN architecture includes a convolutional neural network, a long-term short-term memory network, and a gated recurrent unit for feature extraction. Using a comprehensive dataset of more than 60,000 images, the model distinguishes Tamil alphabet characters with 92% and English alphabet characters with 95% recognition rate.

Multilingual handwritten character recognition presents additional challenges due to diverse scripts, diacritics, and handwriting styles. Existing approaches include classical CNN architectures trained from scratch, as well as attempts to apply transfer learning from pretrained models such as MobileNet or ResNet [14], [15]. However, transfer learning often fails on small, binary datasets due to differences in input channels, image resolution, and feature distribution. Our experiments confirm this limitation, with MobileNet achieving only ~30% accuracy on the merged T-H-E dataset.

Lightweight CNN architectures have recently gained attention for their efficiency and suitability for low-resource environments. Small networks with few convolutional layers, including LeNet-5 (baseline) [3], Depthwise-CNN [14], MiniVGGNet [16], and simple CNNs [17], provide fast training and reasonable accuracy on MNIST, EMNIST, and KMNIST [18]. Such models have been applied to real-time OCR on mobile devices and embedded vision applications [19], [20].

Using small CNNs is particularly advantageous for the T-H-E dataset because the input images are binary, 28×28 pixels, and the dataset size is moderate, reducing overfitting while enabling rapid experimentation. Inspired by these works, we evaluate multiple lightweight CNNs on the merged T-H-E dataset, achieving competitive accuracy with minimal computational cost.

III. MATERIAL AND METHODS

This section describes the dataset, experimental setup, model architectures, and evaluation metrics employed in this study. The goal is to provide sufficient detail for reproducibility and critical evaluation of the methods used for multilingual handwritten character recognition. The dataset preparation includes merging and preprocessing steps designed to reduce class ambiguity while preserving representational integrity across English, Hungarian, and Turkish scripts. Experiments were standardized across multiple lightweight CNN architectures to compare their accuracy and computational efficiency under consistent training conditions. Evaluation metrics focus on performance

at both overall and per-class levels, with attention to common misclassification patterns and resource use.

A. Dataset

For this study, we used the merged and augmented version 5 of the T-H-E dataset [8]. This version merges visually identical upper- and lower-case characters, reducing the total number of classes to 54 and minimizing misclassifications caused by case differences. The dataset contains 152,000 binary (pixel values 0 or 255) handwritten character samples spanning English, Hungarian, and Turkish scripts. Each image is 28×28 pixels.

The dataset was loaded from CSV, normalized to the $[0,1]$ range, reshaped to $28 \times 28 \times 1$ for CNN input, and one-hot encoded for classification. A stratified 90/10 train-test split ensured balanced representation across classes.

B. Experimental Setup

All experiments were conducted on Google Colab using a T4 GPU. To ensure reproducibility across models and runs, random seeds were fixed for NumPy, TensorFlow, and Python's random module. All images were binary and 28×28 pixels, and no color channels or grayscale normalization beyond scaling to $[0,1]$ were applied.

Hyperparameters were standardized across all models to ensure a fair comparison: a learning rate of 3×10^{-4} , batch size of 128, and early stopping with patience of 8 epochs, restoring the best weights. Models were trained from scratch using categorical cross-entropy loss and the Adam optimizer, with up to 100 epochs. A 10% validation split from the training set was used for monitoring early stopping. Training time per model was recorded to compare computational efficiency.

C. Baseline Model

LeNet-5 [3] serves as a classical benchmark for handwritten character recognition. Its architecture includes two convolutional layers with average pooling, followed by fully connected layers and a softmax classifier for the 54 merged character classes. LeNet-5 provides a baseline reference in terms of both accuracy and computational efficiency on small binary images.

D. Lightweight CNN Architectures

The Simple CNN is a minimal, two-convolution-layer architecture designed for speed and efficiency. Each convolutional layer is followed by batch normalization and max pooling, and the dense head consists of a single fully connected layer with 128 units and a dropout of 0.5 before the softmax output. This architecture is intended as a fast and low-parameter reference.

Depthwise-CNN [7] employs three blocks of depthwise separable convolutions with 32, 64, and 128 filters. Max pooling follows the first two blocks, while global average pooling follows the third block. A dense layer of 128 units with dropout of 0.3 precedes the softmax output, maintaining a lightweight yet expressive architecture suitable for small binary inputs.

MiniVGGNet is a deeper variant inspired by VGG16 but smaller in scale. It consists of two convolutional blocks with 32 and 64 filters, each block containing two convolutional layers, batch normalization, max pooling, and dropout. The dense head has 512 units with batch normalization and dropout, followed by a softmax output. While larger than

LeNet-5, Depthwise-CNN, and the Simple CNN, MiniVGGNet provides stronger representational power at the cost of increased parameters and longer training time.

To ensure a fair comparison, all architectures were trained using the same hyperparameters and fixed random seed.

E. Metric Evaluation

Confusion matrices were computed to visualize per-class performance and identify patterns of misclassification. Models were evaluated on the held-out test set using accuracy, precision, recall, and F1-score [21].

Accuracy measures the overall proportion of correct predictions among all instances, providing a straightforward estimate of the model’s general correctness.

Precision quantifies the fraction of true positive predictions over all positive predictions, thus indicating the model’s reliability in identifying positive instances.

Recall (or sensitivity) measures the ability of the model to find all relevant positive cases by calculating the ratio of true positives to all actual positives.

The F1-score, the harmonic mean of precision and recall, balances these two metrics to provide a single value reflecting model performance in cases where class imbalance or asymmetric costs of errors may exist.

The top misclassified class pairs were analyzed to reveal challenges in multilingual character recognition, particularly for visually similar characters and merged upper- and lower-case letters. Training times were recorded to allow direct comparison of computational efficiency versus accuracy across the four architectures.

IV. RESULTS

The proposed lightweight CNN models were evaluated on the merged T-H-E dataset, consisting of 54 classes obtained by merging visually identical upper- and lower-case characters. The dataset comprises binary handwritten character images, which were converted to floating-point format and reshaped into $28 \times 28 \times 1$ arrays. Stratified train/test splits were applied to maintain class distribution across all sets. To ensure a fair comparison, the same random seed (42) was used for all experiments, making the input splits and training initialization identical. Early stopping with a patience of 8 epochs and restoration of the best weights was applied to all models, allowing efficient training while preventing overfitting.

Table 1 summarizes the parameter count, training time, and test accuracy for the four models. Simple CNN and Depthwise-CNN achieved competitive accuracy with minimal computational cost, while MiniVGGNet, a deeper network, achieved the highest accuracy but required almost double the training time. LeNet-5, the classical baseline, had the fewest parameters but longer training time, highlighting the trade-offs between model depth, parameter efficiency, and training speed in small binary datasets.

TABLE I. NUMBER OF PARAMETERS, TRAINING TIME AND TEST ACCURACY OF THE MODELS

Model	Parameters	Training Time (s)	Test Accuracy (%)
Simple CNN	427,702	119.669	91.70

Model	Parameters	Training Time (s)	Test Accuracy (%)
MiniVGGNet	3,091,302	238.387	94.30
Depthwise-CNN	287,204	131.93	92.80
LeNet-5	62,938	363.453	89.50

The results show that lighter architectures achieve impressive accuracy at a fraction of the training time of deeper networks. Depthwise-CNN, with the smallest number of parameters among high-performing models, demonstrates that depthwise separable convolutions efficiently capture discriminative features while remaining computationally light.

Simple CNN achieves nearly the same accuracy as Depthwise-CNN but with slightly more parameters and slightly shorter training time. LeNet-5, despite its simplicity, requires longer training, likely due to fewer convolutional filters and less expressive capacity for capturing subtle variations in handwritten characters.

Detailed analysis of misclassifications reveals systematic patterns in the errors, particularly among visually similar letters or those with diacritic marks. Certain merged or upper/lower-case characters, such as \acute{e}/e , w/W , i/i , and \acute{o}/\acute{O} , were frequently confused across all models. These misclassifications are likely due to insufficient learning of subtle strokes and diacritics in binary images, compounded by the inherent ambiguity in merged classes.

TABLE II. ANALYSIS OF MISCLASSIFICATIONS

True Class	Most Frequent Misclassification	Count	Notes on Visual Similarity
8 (h)	10 (j)	12	Descender similarity
13 (m-M)	32 (ü-Ü)	15	Upper/lowercase merging causes ambiguity
17 (q)	36 (Q)	15	Subtle differences in tail shapes
20 (t)	59 (T)	18	Capitalization confusion
28 (ğ)	53 (Ġ)	15	Diacritic not consistently learned
34 (é)	34 (O)	17	Handwriting variations resemble O
8 (h)	27 (ç)	12	Descenders/hooks create confusion
30 (ş-Ş)	8 (h)	14	Stroke similarity in compact handwriting

These misclassification patterns indicate that while lightweight CNNs efficiently learn general shapes and coarse features, fine-grained distinctions, particularly diacritics and merged letters, remain challenging. MiniVGGNet shows some improvement in resolving these subtle distinctions, but at the cost of longer training and a threefold increase in parameters. The use of a fixed random seed across all experiments ensures that these comparisons are fair, as all models were exposed to the same training and validation splits.

Overall, these results demonstrate that lightweight CNNs, such as Simple CNN and Depthwise-CNN, provide a highly

efficient and reasonably accurate baseline for multilingual handwritten character recognition. While deeper networks can slightly improve accuracy, the efficiency gains of compact models make them especially suitable for low-resource environments or rapid prototyping on binary handwritten datasets. The misclassification analysis further provides insights into which character groups present the greatest challenge, guiding potential improvements such as targeted data augmentation or refined preprocessing for diacritics.

V. CONCLUSION

In this study, we explored the performance and efficiency of four CNN architectures LeNet-5, Simple CNN, Depthwise-CNN, and MiniVGGNet on the merged T-H-E multilingual handwritten character dataset. By using a fixed random seed across all experiments, we ensured a fair comparison of training dynamics, parameter efficiency, and predictive performance. Our results show that lightweight architectures such as Simple CNN and Depthwise-CNN achieve competitive test accuracy while requiring minimal computational resources and training time, making them highly suitable for small binary datasets and low-resource environments.

Detailed analysis of misclassifications revealed that visually similar characters, merged upper- and lower-case letters, and diacritics remain challenging across all models. While MiniVGGNet slightly improved accuracy in resolving these subtle distinctions, it did so at the cost of substantially increased parameters and longer training times. LeNet-5, as a classical baseline, demonstrated the lowest parameter count but relatively slower training and lower accuracy compared to the lightweight CNNs.

Overall, this study demonstrates that careful design of compact CNN architectures can balance efficiency and accuracy for multilingual handwritten character recognition. Our findings provide a practical reference for future research on lightweight models, highlighting the trade-offs between model depth, parameter count, and the ability to capture fine-grained character details. Future work may focus on targeted data augmentation, diacritic-aware preprocessing, or hybrid architectures that further improve recognition of visually similar classes while maintaining computational efficiency.

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Explainable MLP-Based Surrogate Model for Predicting Terahertz Metamaterial Absorber Performance

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Abstract—This study presents an explainable surrogate modeling approach for predicting the absorption behavior of broadband THz metamaterial absorbers based on vanadium dioxide (VO₂) by a Multi-Layer Perceptron (MLP) network. The proposed model was trained on an electromagnetic full-wave simulation dataset, which included design parameters and frequency, with the corresponding absorption as output. The MLP-based surrogate model was evaluated using performance metrics such as the coefficient of determination (R²), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE). Additionally, explainable artificial intelligence (XAI) methods were used to understand how the input parameters affect the absorption. Thus, the proposed model offers important clues regarding the physical relationship between design parameters and absorption performance. The results obtained indicate that the MLP model achieves high prediction accuracy. This approach offers a promising alternative for the design and optimization of next-generation THz absorber devices.

Keywords—absorption, XAI, metamaterial, MLP, SHAP, surrogate modeling, Terahertz.

I. INTRODUCTION

With the development of wireless communication technologies, especially 6G networks, TeraHertz (THz) frequency components have received attention from researchers owing to their potential for ultra-high data rates of up to 1 Tbps and low latency [1], [2]. Metamaterial absorbers have emerged as crucial components due to their ability to selectively absorb electromagnetic waves, thereby enhancing signal quality and reducing interference [3]. They provide control over wave absorption, which is essential for applications in security, imaging, sensing, and privacy technology, as well as in communications [4] - [6]. Among the various materials used in metamaterial component design, vanadium dioxide (VO₂) is notable for its exceptional phase-transition properties [7]. VO₂ experiences a reversible metal-insulator transition near room temperature, thus allowing the electromagnetic response of the absorber to be dynamically tuned [8], [9]. Due to their tunability, VO₂ based metamaterial absorbers can be good candidates for smart communication systems and adaptable THz devices [10], [11].

However, the use of simulation approaches in the design process can make these absorbers costly and time-consuming. Machine Learning (ML) has become a useful technique for addressing these problems by providing faster and more reliable prediction capabilities. A dataset was introduced in [12] to analyze THz metamaterials and train ML models. A data-driven surrogate-assisted model for the design optimization procedure of a metamaterial-based filtenna using deep learning was presented in [13]. Data-driven approaches in metamaterial design have been highlighted in recent research [14], which shows that ML techniques can be used to effectively predict the bandwidth and gain of metamaterial antennas.

A new strategy is needed to build trust in artificial intelligence and ML models. Despite progress in recent decades, interpretability and black box issues remain pervasive [15]. Due to their “Black Box” structure with limitations on their interpretability, ML models are often criticized [16]. Explainable Artificial Intelligence (XAI) addresses these challenges. Understanding the impact of input parameters on the model’s predictions is crucial to ensure interpretability and facilitate effective debugging of the surrogate model [17].

In this work, a Multi-Layer Perceptron (MLP) model integrated with SHapley Additive Descriptions (SHAP), a method from XAI, was used for the interpretable prediction of the absorption performance of a metamaterial absorber. SHAP analysis was used to identify the critical input parameters and their interactions that affected the single output prediction. An MLP model was then developed using this information to improve the prediction performance. The developed model not only makes accurate predictions but also explains their underlying logic, enabling the design of advanced metamaterial absorbers for 6G and other THz applications.

II. UNIT CELL AND DATASET

The unit cell geometry and design parameters presented in [12] are shown in Fig. 1. The design parameters of the unit cell of the metamaterial absorber are important to achieve the desired electromagnetic response. The unit cell design has a periodicity of (a) 13 μm and a dielectric substrate thickness (h) of 6 μm . The metallic and VO₂ layers follow the standard

thicknesses defined in [12]. The structure consists of two concentric rings: the outer ring has an outer radius (R_{O1}) of $6.5 \mu\text{m}$ and an inner radius (R_{I1}) of $5.5 \mu\text{m}$, whereas the inner ring has an outer radius (R_{O2}) of $2 \mu\text{m}$ and an inner radius (R_{I2}) of $1 \mu\text{m}$. The gap between these rings has a width (w) of $1 \mu\text{m}$.

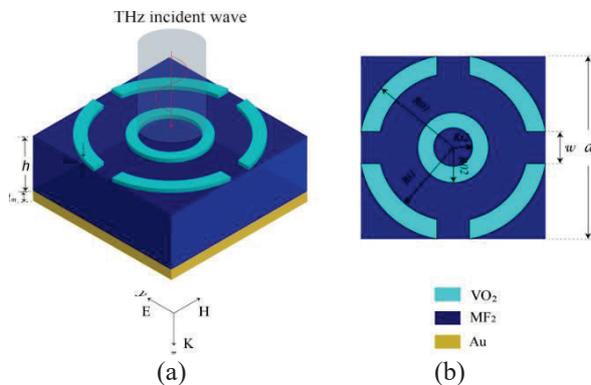


Fig. 1. Schematic of the metamaterial absorber (a) perspective view of the unit cell, and (b) top view [12].

The dataset [18] used in this study was generated through electromagnetic simulations by performing a parameter sweep on the design parameters of a metamaterial absorber's unit cell design, as described in [12]. It is publicly available on Kaggle [18] under the title "Metamaterial Absorber Dataset". The dataset contains three input parameters, as listed in Table I, and an output (absorptance). It comprises a total of 9,018 data points. The presented MLP-based surrogate models were trained on this dataset to predict the absorptance in the operational THz frequency band.

TABLE I. INPUT FEATURES OF THE DATASET [12]

Feature	Symbol	Range	Unit
Patch Width, p	a	11 – 14	μm
Dielectric Thickness, m	h	3 – 8	μm
Frequency	f	0 – 18	THz

III. MLP

Artificial Neural Networks (ANNs) were developed inspired by biological neural networks [19]. MLP is a type of ANNs and consists of fully connected neurons, which communicate with each other in a feedforward manner. MLP networks can perform a wide range of classification and regression prediction tasks with high accuracy or low error. On the other hand, owing to the complex architecture of MLP networks, the internal logic of the network is not understandable or explainable. Black box models are defined as these systems that, when given the correct input, produce the correct output without providing any explanation of how they operate inside [19] - [21].

IV. SHAP

The interpretability or comprehensibility of ML models is as important as their predictive accuracy in several fields [22]. MLP neural networks can deliver superior accuracy predictions but lack interpretability due to their black box

nature. Understanding the influence of input features on model decisions is important because it affects overall confidence in model outcomes. Moreover, it is crucial for their applicability, especially in complex or high-risk fields [16].

In this study, SHAP [23] technique was applied to analyze feature contributions and interpret the predictions produced by MLP models. In this technique, all possible feature subsets are comprehensively evaluated, and a contribution/importance value is assigned to each feature [24]. This assigned value, known as the Shapley value, is the average marginal contribution of a feature value for a specific prediction task [25]. Each feature may have a positive or negative impact on model predictions depending on its SHAP value.

V. EXPERIMENTAL STUDIES

In this work, the Python programming language on the Google Colab platform was used to implement MLP network models for predicting the performance of THz metamaterial absorber. Pandas, Matplotlib, Sklearn, TensorFlow, Keras, and Shap open-access libraries were used. The dataset was split into two parts for training and testing at the most common split rate of 70/30. All data were normalized using the StandardScaler() function.

As shown in Table II, six different MLP models were implemented and tested to determine the best possible network architecture (max. 200 epochs). Adam optimizer was chosen to minimize the loss function "MSE" during the training of the models, and early stopping was applied as a practical and efficient approach to prevent overfitting.

TABLE II. MLP NETWORK CONFIGURATIONS

Model	Network Structure
MLP-N1	Dense (64) - Activation = ReLU Dropout (0.2) Dense (32) - Activation = ReLU Dense (1) - Activation = Linear
MLP-N2	Dense (64) - Activation = ReLU Dropout (0.2) Dense (1) - Activation = Linear
MLP-N3	Dense (64) - Activation = ReLU Dense (32) - Activation = ReLU Dense (1) - Activation = Linear
MLP-N4	Dense (32) - Activation = ReLU Dropout (0.2) Dense (1) - Activation = Linear
MLP-N5	Dense (128) - Activation = ReLU Dense (32) - Activation = ReLU Dropout (0.2) Dense (1) - Activation = Linear
MLP-N6	Dense (128) - Activation = ReLU Dense (32) - Activation = ReLU Dense (1) - Activation = Linear

Popular metrics (MSE, RMSE, MAE, and R^2) were utilized to assess these network models' performance. Table III presents the prediction results for the MLP models. All the MLP models performed well despite the small number of features and MLP-N6 achieved better performance.

TABLE III. COMPARATIVE EXPERIMENTAL RESULTS

Model	R ²	MSE	RMSE	MAE
MLP-N1	0.9972	0.0004	0.0201	0.0148
MLP-N2	0.9611	0.005569	0.074627	0.059645
MLP-N3	0.9987	0.000190	0.013767	0.007489
MLP-N4	0.9182	0.011723	0.108273	0.090534
MLP-N5	0.9968	0.000459	0.021433	0.015662
MLP-N6	0.9989	0.000164	0.012809	0.007241

Fig. 2 (a) and (b) show the training/validation MSE (loss) and training/validation MAE curves for the MLP-N6 model, respectively. Both the training MSE and MAE values steadily decreased across epochs (see Fig. 2), indicating that the model learned effectively. In addition, the parallel decrease in the training and validation MAE curves confirmed the generalization ability of the model.

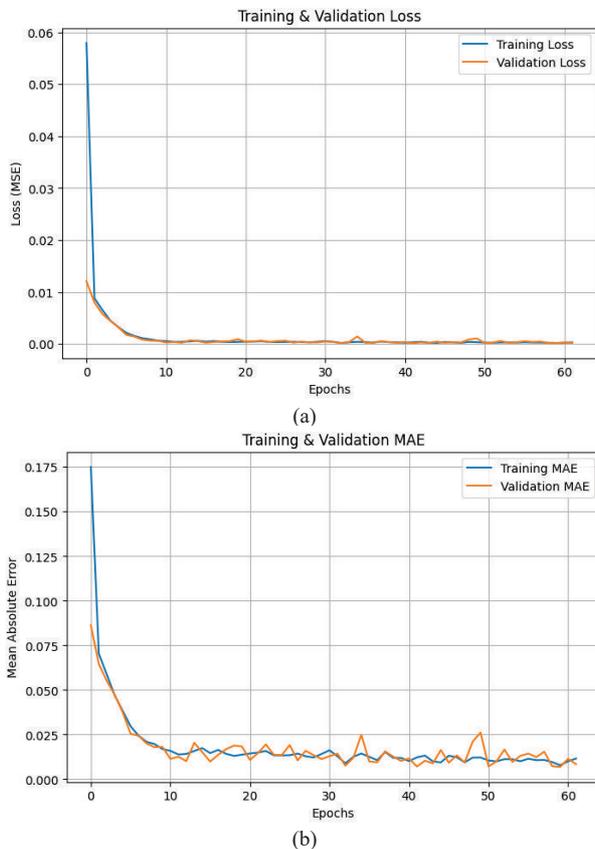


Fig. 2. Training and validation a) loss and b) MAE curves throughout epochs for MLP-N6

TABLE IV. PERFORMANCE COMPARISON

Ref.	Model	R ²	MSE
This study	MLP-N3	0.9987	0.000190
	MLP-N6	0.9989	0.000164
[12]	Bagging Regressor	0.9985	0.000212
	Random Forest Regressor	0.9984	0.000226

Table IV gives a comparison of the prediction models for the same dataset. Analyzing Table IV, it is concluded that this study achieved better results (the highest R² and the lowest error values) than the best results reported in [12].

SHAP analysis was applied to the MLP models to quantify the feature contributions. Fig. 3 illustrates the SHAP summary plot for the trained MLP-N6 model. In the plot, the color gradient, ranging from blue (low) to red (high), indicates the feature values. Frequency had the highest impact on the model predictions, followed by *a* and *h*.

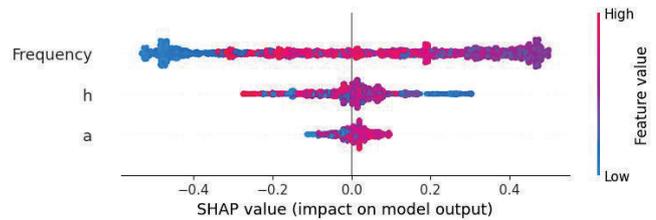


Fig. 3. SHAP summary plot.

Fig. 4 presents the SHAP bar plot for a test sample. This plot visualizes the contribution of each feature to absorbance prediction. A positive SHAP value indicates that the feature improves prediction. All features contributing to the absorption prediction had positive SHAP values, and frequency had the largest positive contribution. By providing transparency in model decision-making, the black box challenge of MLP was addressed.

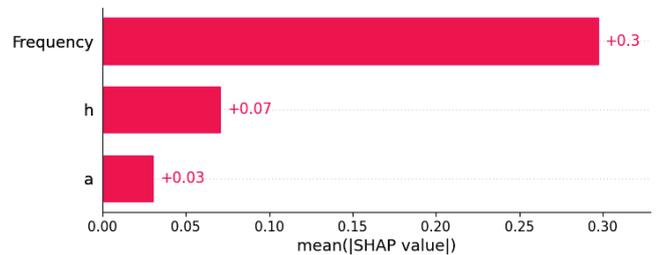


Fig. 4. SHAP bar plot for a sample.

CONCLUSION

In this work, the absorption performance of THz metamaterial absorbers was predicted using a simulation-driven dataset. We investigated an explainable surrogate model that integrates SHAP and MLP. Six different MLP network models were tested, and SHAP technique was leveraged to understand MLP model decisions. Explainability can be used to improve model structure and performance. The contribution of this study lies in the proposed method, which highlights the impact of physical design parameters on absorbance. These findings suggest that the use of explainable frameworks may also be effective in designing other electromagnetic components. This suggests that, during the design process, researchers can benefit from integrating XAI-enhanced machine learning methods to enable rapid evaluation, reduce development time, and ultimately carry out a more efficient workflow.

In future work, the predictive performance of the current surrogate model can be further refined by applying hyperparameter tuning for the MLP architecture, including neurons per layer, activation functions (ReLU, tanh), and optimizers (Adam, SGD), etc. In addition, future studies may focus on the inverse design and various analyses of XAI.

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Exploring the Applications of Artificial Intelligence in Sulfur Recovery Units: A Review

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Abstract—The Sulfur Recovery Units, particularly the Claus process, are critical in the natural gas and petroleum industries for recovering sulfur from hydrogen sulfide (H_2S) and other sulfur compounds. Even if traditional methods have been employed for decades, the integration of Artificial Intelligence (AI) is applied to sulfur recovery recently in the aim of improving efficiency, reducing costs, and enhancing environmental compliance. This literature review examines the key applications and contributions of AI in the sulfur recovery process. The results show that from conceptual constructs for adaptive controls, artificial intelligence became an effective driver of process intelligence in sulfur recovery units. This new era of AI is characterized by deep learning, transfer learning, and hybrid modeling that allow for accurate prediction, improved emission control, and robust optimization under uncertain process conditions. The studies examined show consistent progress from neural estimators to autonomous, interpretable SRU systems that can adapt in real time.

Keywords—Claus process, artificial intelligence, machine learning, sulfur recovery

I. INTRODUCTION

Sulfur recovery units are essential for treating sour gases and meeting environmental regulations. Their main function is to recover elemental sulfur from H_2S via the Claus process and related tail-gas treatment operations. Fig.1 illustrates a typical Sulfur Recovery Unit (SRU), where hydrogen sulfide (H_2S) is partially oxidized in the reaction furnace to form sulfur dioxide (SO_2) and elemental sulfur [1]. The process gases then pass through condensers and catalytic reactors to convert remaining H_2S and SO_2 into sulfur, which is collected while the tail gas is treated to reduce emissions.

Monitoring and control of key variables such as conversion efficiency, SO_2 concentration, and temperature are crucial yet challenging due to high temperature, process coupling, and sensor limitations. Traditional first-principle models often fail to capture dynamic nonlinearities.

Recent advances in artificial intelligence (AI)—including machine learning (ML), deep learning (DL), and hybrid approaches—have enabled data-driven “soft sensors” capable of estimating unmeasured variables and improving predictive control accuracy.

This review consolidates state-of-the-art research on AI techniques in SRUs and similar chemical process environments, highlighting progress from early neural networks to modern transformer-based and transfer-learning frameworks in the years 1994-2025.

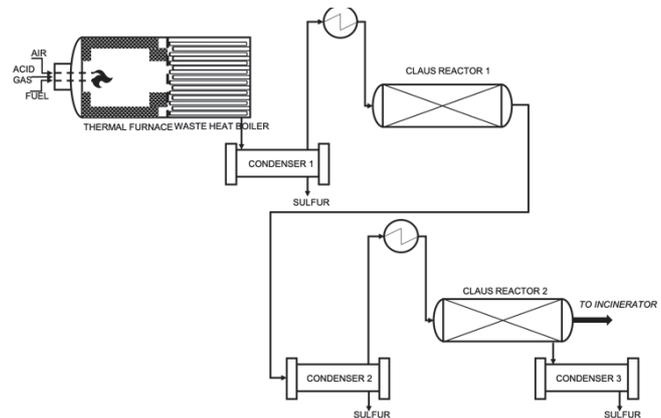


Fig. 1. Basic scheme of a sulfur recovery unit.

II. LITERATURE REVIEW

Table 1 provides the review of the literature investigates the evolution of AI in sulfur recovery units from early adaptive control and basic soft sensors in the 1990s to advanced deep learning, transformer, and graph-based models in 2025. Approaches include neural networks, autoencoders, ensemble methods, transfer learning, and reinforcement learning through which accurate soft sensing, process optimization, and real-time monitoring is possible. Recent findings highlight robustness, interpretability, semi-supervised learning, and hybrid knowledge-data integration approaches as new trends to address complex, dynamic, and multivariate SRU processes.

Progression of predictive performance in AI-based sulfur recovery unit (SRU) models from 1994 to 2025 is given Fig.2. Early adaptive control approaches achieved limited precision but established the foundation for intelligent process control. Over the following decades, accuracy improved steadily with the introduction of neural networks, ensemble learning, and hybrid deep learning architectures. Recent demonstrate predictive accuracies approaching 99% in dynamic SRU environments.

A. Early Developments: Adaptive and Neural Control

The earliest AI-related SRU control effort was by Cunningham [2], who applied adaptive control to stabilize Claus process operations and improve sulfur yield. This study laid the groundwork for data-driven process automation. In the early 2000s, Fortuna et al. [3] proposed neural-network-based soft analyzers for real-time estimation of unmeasured variables, demonstrating the feasibility of intelligent monitoring. These pioneering efforts established the conceptual basis for integrating AI with process control systems.

TABLE I. REPRESENTATIVE STUDIES ON AI-BASED SRU AND PROCESS SOFT SENSING

Ref.	Year	Focus/Objective	Method/Model	Key Findings	Contribution to AI in SRUs
[2]	1994	Improve SRU operation stability and sulfur yield.	Adaptive control algorithm.	Demonstrated robust process regulation via adaptive control.	Laid the foundation for intelligent control in SRUs.
[3]	2003	Develop real-time analyzers for process monitoring.	Neural network-based soft analyzers.	Enabled accurate estimation of unmeasured SRU variables.	Introduced soft sensing to SRU process control.
[4]	2014	Estimate optimal sulfinol concentration in gas treatment.	Stabilized MLP with regularization.	Improved robustness and accuracy of gas treatment modeling.	Demonstrated neural model adaptability applicable to SRUs.
[5]	2015	Enhance chemical process quality prediction.	Selective ensemble of local PLS models.	Improved prediction accuracy under varying conditions.	Provided ensemble modeling strategies for SRU soft sensors.
[6]	2017	Design adaptive soft sensors for time-varying processes.	Gaussian Process Regression with time-delay reconstruction.	Enhanced adaptability to dynamic process changes.	Enabled dynamic modeling approaches for SRUs.
[7]	2018	Monitor SRU quality under changing conditions.	Multi-State-Dependent Parameter model.	Achieved accurate soft sensing for sulfur recovery.	Strengthened adaptive quality monitoring in SRUs.
[8]	2019	Improve refinery quality monitoring with AI.	Regression Neural Network.	Enhanced model accuracy with optimized training.	Advanced data-driven quality estimation relevant to SRUs.
[9]	2019	Optimize SRU operation and reduce energy use.	Multi-objective optimization with reaction kinetics.	Minimized energy consumption while maintaining conversion efficiency.	Showed optimization benefits using AI modeling in SRUs.
[10]	2020	Predict industrial quality variables.	Stacked Enhanced Autoencoder.	Extracted deep nonlinear features for accurate prediction.	Advanced data-driven feature learning for SRU sensors.
[11]	2020	Model SRU soft analyzers with deep learning.	Stacked Isomorphic Autoencoder.	Provided reliable estimation of SRU key process parameters.	Applied deep architectures to SRU soft analyzer design.
[12]	2021	Improve interpretability of soft sensors.	Evolutionary Multi-objective Optimization.	Achieved balanced trade-off between accuracy and transparency.	Enhanced explainable AI frameworks for SRU modeling.
[13]	2021	Develop dynamic soft sensors for SRUs.	Echo-State Network (ESN).	Captured temporal correlations in SRU dynamics.	Introduced reservoir computing for SRU variable prediction.
[14]	2021	Assess soft sensor transferability across processes.	RNN and LSTM architectures.	Validated reusability and adaptability across datasets.	Promoted cross-process generalization for SRUs.
[15]	2023	Simplify H ₂ S thermal conversion kinetics.	Machine-learning reduced kinetic model.	Provided fast and accurate process simulation.	Applied ML-based kinetic modeling to SRU reactors.
[16]	2023	Model multivariate soft sensor relationships.	Balanced Mixture-of-Experts (MoE).	Improved feature learning and correlation handling.	Enhanced SRU soft sensor performance with MoE framework.
[17]	2023	Integrate domain knowledge with ML.	Contextual Mixture-of-Experts.	Increased prediction interpretability and reliability.	Promoted hybrid knowledge-data-driven modeling in SRUs.
[18]	2024	Study adversarial attacks on industrial soft sensors.	Mirror Output Attack & Translation Mirror Output Attack.	Identified vulnerabilities in NN-based sensing systems.	Strengthened AI model security for SRUs.
[19]	2024	Enhance transfer learning for process modeling.	Parallel SAE with transfer-incremental learning.	Improved adaptability to varying SRU conditions.	Advanced continuous learning for SRU optimization.
[20]	2024	Design predictive soft sensors.	Multi-step-ahead Hankel Dynamic Mode Decomposition.	Enhanced SRU prediction accuracy and control readiness.	Enabled proactive process control in SRUs.
[21]	2024	Model composite dynamic systems.	Layer-wise residual-driven learning.	Captured fast and slow process dynamics effectively.	Improved multi-scale SRU process modeling.
[22]	2024	Enhance LSTM reliability for noisy data.	Information Filtering Unit-based LSTM.	Improved robustness in signal processing.	Strengthened time-series learning in SRU soft sensors.
[23]	2024	Handle label scarcity in SRU modeling.	ISSA-VMD-ESN semi-supervised hybrid.	Achieved high accuracy with limited supervision.	Extended AI usability in low-data SRU environments.
[24]	2024	Improve nonlinear modeling for soft sensing.	Distributed Nonlinear Bi-LSTM.	Enhanced representation of nonlinear SRU features.	Advanced deep recurrent modeling for SRU prediction.
[25]	2024	Integrate AI-based reconciliation into SRU control.	State-Dependent Parameter + Regression Filter.	Reduced process control errors.	Improved SRU stability and closed-loop performance.
[26]	2024	Model spatiotemporal causality in industrial systems.	Knowledge-Data Guided Reinforcement Learning.	Captured temporal causal dependencies.	Applied RL for adaptive SRU control and optimization.
[27]	2024	Predict SO ₂ emissions in SRU incinerators.	AI-based forecasting model.	Accurately predicted emission patterns.	Supported sustainable SRU emission control.
[28]	2024	Model dynamic processes for soft sensing.	TCN-CBAM-LSTM hybrid model.	Improved temporal feature extraction.	Strengthened sequential learning for SRUs.
[29]	2025	Develop transferable soft sensors.	Graph-based Predictable Deep Transfer Network.	Achieved strong cross-domain adaptability.	Advanced knowledge transfer for SRU AI models.
[30]	2025	Extract global dynamic features from industrial data.	Autoencoder with hidden layer enhancement.	Improved dynamic feature representation.	Enhanced data-driven dynamic modeling in SRUs.
[31]	2025	Address nonlinear time-delay processes.	LASSO Transformer Network.	Increased interpretability and forecasting precision.	Applied transformer-based deep learning to SRUs.

[32]	2025	Implement AI-driven control optimization.	AI Surrogate Model.	Improved operational efficiency and control stability.	Introduced direct AI control frameworks for SRUs.
[33]	2025	Improve online sensing accuracy.	Adaptive Multilevel Regression Integration.	Achieved real-time error compensation.	Enhanced SRU process adaptability and monitoring.
[34]	2025	Continuously predict industrial quality indices.	Deep Temporal Feature Extraction with Ensemble Modeling.	Maintained accuracy under dynamic process drift.	Improved adaptive SRU model updating mechanisms.
[35]	2025	Generate virtual sensor data.	Self-Attention Embedded StyleGAN.	Created realistic synthetic data for training.	Expanded SRU datasets for robust AI learning.
[36]	2025	Design robust soft sensors under input collinearity.	Finite-time delay and regressor identification.	Identified optimal input regressors for modeling.	Refined AI-based SRU sensor design strategies.

MLP: multilayer perceptrons; PLS: partial least squares; RNN: Recurrent Neural Network; LSTM: long short-term memory network; SAE: Stacked Autoencoders; ISSA: Improved sparrow search algorithm; VMD: Variational mode composition; TCN: Temporal convolutional network; CBAM: Convolutional block attention module; LASSO: Least absolute shrinkage and selection operator transformer; GAN: Generative adversarial network

B. Emergence of Soft Sensors and Hybrid Estimation

The next phase focused on soft sensors—virtual models estimating difficult-to-measure variables using historical data. Garmroodi Asil and Shahsavand [4] and Shao and Tian [5] developed multilayer perceptron and ensemble regression models to improve robustness in chemical process prediction. Bidar et al. [7] extended this concept to sulfur recovery monitoring via multi-state-dependent parameter models, achieving improved adaptability. Deep learning architectures such as Gaussian Process Regression [6] and autoencoders [10], [11] further enhanced nonlinear feature extraction and dynamic modeling.

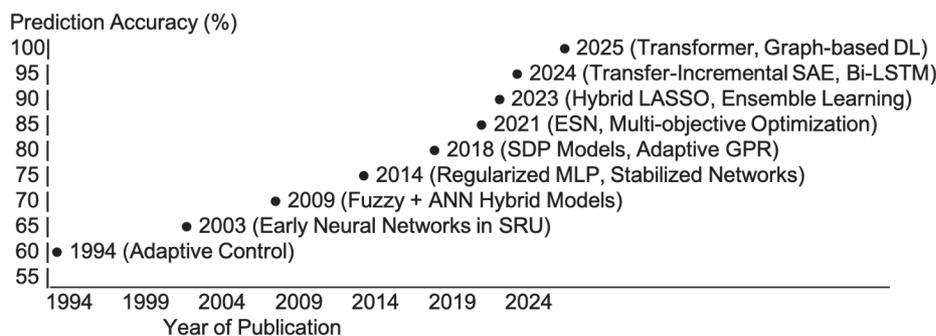


Fig. 2. Progression of predictive performance in AI-based sulfur recovery unit (SRU) models from 1994 to 2025.

C. Advancements in Dynamic Modeling and Deep Learning

Between 2021 and 2024, SRU modeling shifted toward recurrent and reservoir computing. Patané and Xibilia [13] and Curreri et al. [14] adopted echo-state networks (ESN) and long short-term memory (LSTM) architectures to capture dynamic temporal patterns, enabling predictive control. Concurrently, Huang et al. [16] and Souza et al. [17] introduced mixture-of-experts (MoE) frameworks, integrating data-driven and domain-based reasoning for improved interpretability.

In parallel, Dell'Angelo et al. [15] utilized machine learning to simplify kinetic modeling of H₂S thermal conversion, allowing faster process simulations. Security and robustness concerns were also addressed—Chen et al. [18] examined adversarial attacks on soft sensors, revealing vulnerabilities in neural monitoring systems, while Talaei et al. [25] proposed regression-based reconciliation filters to mitigate sensor noise and ensure reliable control.

Deep transfer learning was another milestone. Mou et al. [19] and Zhang et al. [21] designed transferable soft sensors capable of learning across different process domains, significantly reducing retraining needs. Wang &

Simultaneously, optimization-driven AI systems began emerging. Rahman et al. [9] applied multi-objective optimization to minimize SRU energy use without compromising conversion efficiency, while Yuan et al. [11] introduced stacked autoencoders to capture deep correlations between process variables. These studies demonstrated that AI can outperform traditional empirical or first-principles models when addressing data-driven nonlinearities.

Li [23] extended into the problem of label scarcity by using semi-supervised hybrid architectures and enhanced reliability in the scenario of underdeveloped data.

D. Recent Innovations: Reinforcement Learning and Generative AI

Recent contributions emphasize reinforcement learning (RL) and generative AI for intelligent SRU operation. Zhang et al. [26] applied RL to model spatiotemporal causality in industrial systems, providing adaptive control strategies for SRUs. Thameem et al. [27] developed AI-based emission forecasting to predict SO₂ release from SRU incinerators, supporting regulatory compliance and sustainability.

Emerging generative models, such as the StyleGAN-based framework by Zhang et al. [35], produced realistic virtual sensor data to augment training datasets. Such synthetic data generation enhances model generalization in low-sample environments. Meanwhile, transformer architectures like the LASSO Transformer Network [31] and hybrid TCN-CBAM-LSTM models [28] improved sequential learning and interpretability. Finally, recent contributions by Liu et al. [32], Wu et al. [33], and Zhao et al. [34] demonstrated adaptive multilevel regression and surrogate modeling for online error compensation, marking the newest phase in real-time AI-driven SRU monitoring.

III. DISCUSSION

The literature review shows a clear transition from early static neural models to hybrid deep architectures, where knowledge, optimization, and domain adaptation are merged. The main trends include:

- Improved Model Generalization: With multi-objective optimization and ensemble learning.
- Dynamic Adaptation: Via recurrent and transfer learning networks.
- Interpretability and Trust: Improved using regularization and feature selection frameworks.
- Operational Integration: Surrogate models allow for real-time process control and emission prediction.

However, challenges persist. Most studies are based on limited industrial datasets and lack benchmark comparisons. For black-box architectures, model explainability is limited. Furthermore, deployment in safety-critical SRUs requires robust validation, cybersecurity, and adaptive maintenance strategies.

IV. CONCLUSION

Artificial intelligence technology has rapidly changed sulfur recovery units' modeling and control, and has increased predictive power, flexibility, and environmental compliance. With AI-driven soft sensors and surrogate models, it is possible to monitor the important process variables in ways that traditional measurements would be challenging to do. Though interpretability and industrial validation are challenging, the integration of hybrid and deep learning architectures marks a significant advancement in SRU technology. Further studies blending AI, process knowledge, and sustainable operation principles will be essential to ensure the next generation of intelligent SRUs.

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Development of AI-Based Surveillance Software

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Abstract—This paper presents the development of an intelligent video surveillance software designed to perform real-time processing of security camera footage. The system combines motion detection, object detection, and tracking to separate relevant activities from background variations. A web-based interface was designed to support camera management and recording access. Results from a 30-day test with four cameras showed that the software reduced storage usage by approximately 98.4% compared to continuous recording. The system was also able to process video in real-time at 10 FPS per camera. This makes multi-camera monitoring both efficient and user-friendly by recording only when activity (e.g., a person) is detected within user-defined zones and allowing easy event filtering.

Keywords—artificial intelligence, video surveillance, real-time processing, motion detection, object detection, object tracking

I. INTRODUCTION

Video surveillance has long been an important part of security, helping to keep lives and property safe. These systems are now widely used in both public and private areas, and the resulting video data can pose challenges for storage, processing, and management. Continuous recording from numerous cameras consumes a large amount of storage and can be difficult to review afterward. Manual video monitoring relies on human operators, which is expensive, time-consuming, prone to error, and difficult to oversee when there are many cameras [1].

Advances in machine vision and artificial intelligence enable automatic filtering and highlight relevant details. This reduces storage usage, as only important activities are recorded, and makes it easier for operators to review footage, even with multiple cameras. Intelligent video surveillance systems are capable of detecting motion in real time, recognizing and classifying objects, and tracking their movements. This reduces the possibility of human error, speeds up response times in emergencies, and makes the system easily scalable, meaning that larger areas and more cameras can be monitored effectively [2], [3].

These advancements motivate the development of software capable of efficiently processing multiple video streams and extracting information relevant to security monitoring. The main problem addressed in this paper is how a video surveillance system could be implemented that is capable of processing video streams from multiple cameras in real time, detecting and tracking relevant objects, and selectively recording events within user-defined zones, while minimizing computational requirements.

To address this problem, the objectives of the work are as follows:

- Ensure real-time processing of multiple video streams.
- Detect and track objects (e.g., people or vehicles) in monitored zones.

- Implement selective recording based on motion and zone definitions.
- Provide a user interface for monitoring video streams, managing recorded events, and playback.

A. Overview of Relevant Technologies

1) Motion Detection Methods

Motion detection is a fundamental area of machine vision, which involves identifying changes in the position of objects relative to their background. It plays an important role in many areas of application (e.g., intelligent video surveillance, traffic monitoring). In motion detection, it is necessary to distinguish between what is static (background) and what is moving (foreground) [4].

a) Frame Differencing

This is traditional and one of the simplest solutions. It takes the difference between two consecutive frames. Among the discussed methods, it requires the least computational resources. Its disadvantage is that it cannot accurately identify the entire contour of a moving object [4]. Results are noisy. Blurring and various morphological operations (e.g., closing) can be used to remove noise and improve the quality of motion detection [5].

b) Temporal Differencing

This is based on the temporal difference between consecutive frames, pixel by pixel, focusing on changes over time. It does not give good results if the object to be detected moves too slowly or too quickly, because in these cases the difference between frames is very small. It is capable of handling sudden changes in lighting conditions in indoor environments [4].

c) Optical Flow

One of the most computationally intensive methods among traditional solutions. In this case, motion detection is based on estimating the optical flow field of the image and then clustering based on the optical flow distribution of the video frames. It is memory-intensive, requires complex calculations, and is sensitive to noise [4]. Similar to Frame Differencing, a significant part of the noise can be removed with blurring and morphological operations, thus improving the quality of the motion detection [6].

d) Background Subtraction

One of the simplest and most reliable motion detection methods. A reference frame (background model) is given. The difference between the current frame and the reference frame is calculated. The resulting image shows the moving object. It is not suitable for handling dynamically changing backgrounds [4]. The reference frame can be updated over time, allowing changes in the background to be tracked. In such cases, the noise can remain minimal [7].

2) Object Detection Methods

Object detection is a key area of computer vision that is essential to many applications (e.g., self-driving vehicles, pedestrian and face recognition). Object detection techniques can be divided into two main groups: traditional methods, which use various machine learning techniques, and deep learning-based approaches [8].

a) Traditional Solutions

Before the advent of deep learning, object detection relied on manually extracted features with classical machine learning algorithms. Human expertise was key in selecting relevant features. Main methods include General Hough Transform (Ballard D, 1981), Harris Corner Detector (1988), and SIFT (Scale-Invariant Feature Transform, Lowe, 2004) [8].

b) Deep Learning-Based Methods

Deep learning techniques require less manual feature extraction and perform better with large datasets. They can independently learn features, adapt to environmental conditions, and detect multiple objects in real time. R-CNN (Region-based Convolutional Neural Networks) architectures (e.g., R-CNN, Fast/Faster/Mask/Cascade R-CNN) follow a two-stage process: region proposal and then object detection on the proposed regions [8], [9]. YOLO (You Only Look Once) and SSD (Single Shot Detector) architectures perform detection in a single step eliminating the need for a separate regional proposal stage [10].

Based on a comparative analysis conducted by *Subbiah et al.* [11], the YOLO architecture performs well in real-time surveillance, as it can detect objects quickly without much loss in accuracy. Although certain R-CNN models can achieve higher accuracy, their processing times are longer, making them less suitable for real-time applications.

B. Test Environment Overview

Four cameras were installed on a suburban residence to monitor critical areas of the property: Entrance Gate, Terrace, Rear Garage, and Front Garage. Fig. 1 shows the location and coverage areas of the surveillance cameras.



Fig. 1. Camera placement on the property. Top-left: Front Garage; Top-right: Entrance Gate; Bottom-left: Rear Garage; Bottom-right: Terrace. (Public areas masked in black.)

II. METHODS

The system consists of four Hikvision DS-2CE16H0T-IT3F analog cameras connected by coaxial cables to a central Hikvision DS-7204HTHI-K1 DVR. The DVR streams video over the network at a resolution of 5 MP (2560×1944 px), 20 FPS, with a constant bitrate of 12,288 Kbps and H.264 encoding. Processing is performed by a high-performance computer running Windows 11, with an Intel Core i7-13700K CPU, Nvidia GeForce RTX 4090 GPU, and 32 GB of RAM.

The software was implemented in C# using the .NET Core framework. Motion detection, object detection, and tracking algorithms run on the backend, and the processed data is transmitted via a JSON API to a web-based Blazor interface, where it is displayed and user interactions occur.

Live video data is streamed from the installed cameras using the RTSP protocol. Several NuGet packages were used. For computer vision tasks and camera access, the OpenCV .NET wrapper EmguCV [12] was utilized. YOLO object detection was implemented using YoloDotNet [13]. The Jonker-Volgenant algorithm for object tracking was applied via the LapjvCSharp package [14]. For image manipulation and rendering, SkiaSharp was employed [15].

The base structure of the system, which is executed for each frame that needs to be processed, is illustrated in Fig. 2.

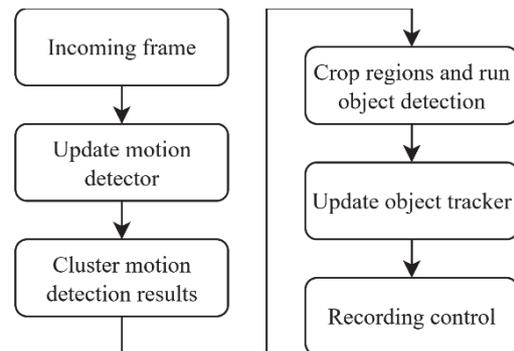


Fig. 2. Block diagram of the base process, which executes on every frame to be processed. Video frames update the motion detector, generating motion boxes that are clustered into detection regions. These regions are processed by the object detector, producing bounding boxes, labels, and confidence scores, which update the centroid-based tracker. Recording is triggered when an active object with the target label is detected and stopped after a set period of inactivity.

Fig. 3 presents a frame with motion boxes (blue), detection regions (green), and detected object bounding boxes (red).

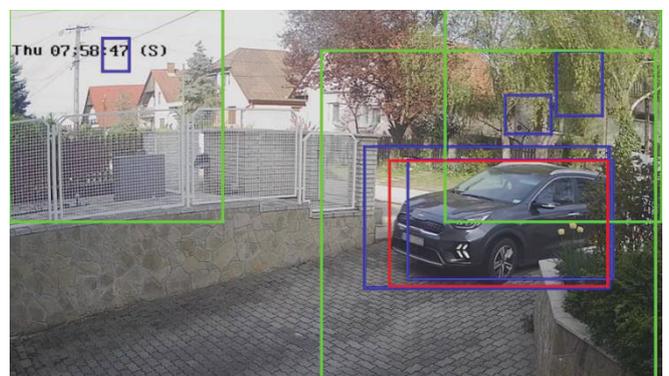


Fig. 3. Frame illustrating the motion detection and object detection process. Blue boxes indicate areas of detected motion, green boxes represent clustered detection regions derived from nearby motion, and red boxes show the bounding boxes of objects identified by the object detection algorithm.

Fig. 4 shows the image sections corresponding to the three detection regions shown in Fig. 3 used for object detection. In Fig. 4(a), no objects were detected. In Fig. 4(b) and Fig. 4(c), the same vehicle was detected in both regions. The object tracker associated these detections with the same vehicle, resulting in a single tracked object.

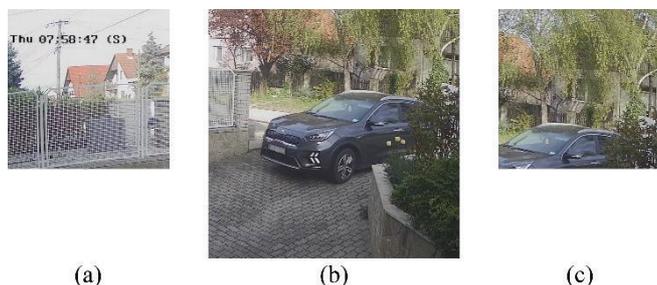


Fig. 4. Image sections of the detection regions shown in Fig. 3, cropped from the original frame for object detection. (a) No objects detected; (b) and (c) the same vehicle detected.

A. Zones and Motion Masks

Users can define motion masks and zones on the cameras by specifying polygon vertices, as illustrated in Fig. 5. Motion detection is disabled in areas covered by motion masks, thereby reducing resource usage. If at least one zone is defined, the system records only events occurring within that zone. Each zone can be named, and the object types of interest (e.g., *person* and *car* labels) can be specified.



Fig. 5. Example of a motion mask and a zone named “test_zone.” Zone vertices (blue) and motion mask vertices (red) are specified by their (x, y) coordinates. The black area formed by the red vertices represents the motion mask, while the blue area formed by the blue vertices represents the zone. The image coordinate system has its origin at the top-left corner $(0, 0)$ and extends to the bottom-right corner $(2560, 1944)$.

An object is considered within a zone if the bottom-center of its bounding box lies inside or on the edge of the zone, determined using EmguCV’s [12] *PointPolygonTest* function. It returns +1 (inside), -1 (outside), or 0 (on an edge).

B. Motion Detection

From the relevant technologies introduced previously, considering the requirements of real-time processing for motion detection, the Background Subtraction method was selected, specifically using the Running Average [16] technique. This means that newly arriving frames are not compared to a pre-recorded static reference image (e.g., the first frame received), but to a continuously updated moving

average image that is adjusted to the incoming frames with a small weight. This approach allows the background to dynamically follow slower changes in the environment while detecting objects that appear suddenly (e.g., moving people or objects) as foreground.

During the preprocessing of the incoming video frames, the images undergo grayscale conversion and are then resized to 100 pixels high while maintaining the aspect ratio. Optionally, contrast enhancement is performed, followed by a motion mask to filter out uninteresting areas, and Gaussian filtering to reduce noise. The background for motion detection is modeled using a moving average image, which is updated with exponential weighting ($\alpha = 0.01$, during calibration $\alpha = 0.2$). The difference between the current frame and the background model is computed. This difference is then thresholded and dilated. Contours that are too small are discarded, keeping only relevant movements, from which motion boxes are formed. The size of the boxes is scaled back to the original image size. Calibration starts when motion affects a significant part of the frame; during calibration, the background model is updated at an accelerated rate until a stable state is restored. The process is illustrated in Fig. 6.

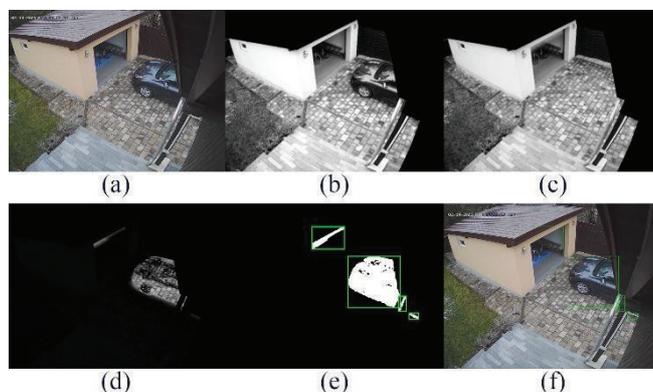


Fig. 6. Steps of motion detection from incoming video frames: (a) original frame, (b) grayscale conversion, resizing, optional contrast enhancement, motion mask application, and Gaussian filtering, (c) background model (moving average), (d) absolute difference between the current frame and the background model, (e) binary mask after thresholding and dilation with significant contours highlighted, (f) final motion boxes scaled to the original frame size.

Detected motion boxes are clustered to reduce redundancy and to prepare for subsequent object detection. Each region is expanded by a scaling factor around the boxes, and overlapping boxes are merged. Each cluster is ensured to be at least as large as the input size of the detection model. The system output comprises detection regions, each containing one or more motion boxes. The process is illustrated in Fig. 7.

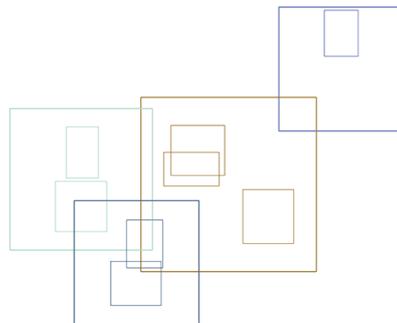


Fig. 7. Motion boxes are grouped into clusters, each forming a detection region. Different colors indicate clusters; boxes in the same cluster share the same color.

C. Object Detection

Object detection is performed on the detection regions obtained from motion detection. Each region is cropped from the original frame and processed using the YoloDotNet package [13] with the pre-trained YOLOv12s model [17]. Detections are filtered by class labels and confidence thresholds, and bounding boxes are mapped back to the original frame coordinates. If a detected object lies near the edge of the detection region in which it was detected, the region is expanded, and detection is repeated. Overlapping detections are resolved using Non-Maximum Suppression (NMS), and highly overlapping duplicates are removed. The output includes the object class, confidence score, bounding box, and the corresponding detection region, which is then used for object tracking based on bounding box centroids.

D. Object Tracking

The main purpose of object tracking in this system is to determine whether an object becomes stationary, such as a parked vehicle. Several solutions can be used to track recognized objects. Due to real-time processing, a simpler technique was chosen, which tracks objects based on the centroids of the bounding boxes surrounding them (centroid object tracking [18], [19]). The tracking result for a passing vehicle is illustrated in Fig. 8.

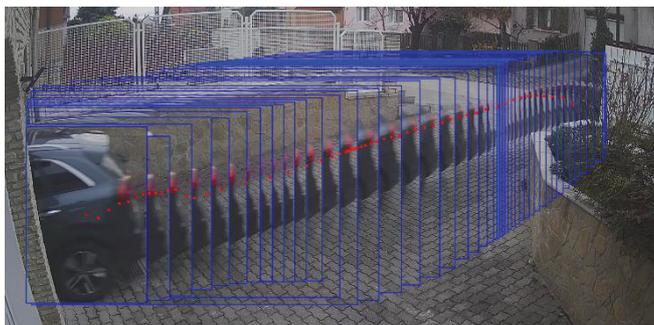


Fig. 8. Tracking of a vehicle over 56 consecutive frames. Blue rectangle: detected object; red dot: centroid used for tracking. The tracker updates object positions frame by frame by matching centroids of detected objects to previously tracked objects, handling entries, exits, and temporary occlusions.

The object tracker receives the object detection results (bounding boxes, labels, and confidence scores) for each processed frame. Let the set of currently tracked objects be

$$T = \{ T_1, T_2, \dots, T_m \} \quad (1)$$

and the set of detected objects in the current frame be

$$D = \{ D_1, D_2, \dots, D_n \} \quad (2)$$

where m and n are the numbers of tracked and detected objects, respectively. Each tracked object T_i and detected object D_j has a centroid $c_{T_i}, c_{D_j} \in \mathbb{R}^2$. A cost matrix $C \in \mathbb{R}^{m \times n}$ is constructed using the Euclidean distances between the centroids:

$$C_{ij} = \|c_{T_i} - c_{D_j}\|_2, i=1, \dots, m, j=1, \dots, n \quad (3)$$

The assignment problem aims to match detected objects to tracked objects to minimize total cost. This is formulated as a Linear Assignment Problem (LAP) and can be efficiently solved using the Jonker-Volgenant algorithm [20] applied via

the LapjvCSharp package [14]. The solver outputs an assignment array:

$$x[i], i=1, \dots, m \quad (4)$$

where $x[i]$ is the index of the detected object assigned to tracked object T_i . If no detection is assigned to T_i , then $x[i] = -1$. Using these assignments, each tracked object is updated with information from the corresponding detected object.

In practical scenarios, the number of detected objects may differ from the number of tracked objects ($n \neq m$):

1. More detected objects than tracked objects ($n > m$): New objects enter the scene. Unassigned detected objects are initialized as new tracks.
2. Fewer detected objects than tracked objects ($n < m$): Objects leave the scene or become occluded. Unassigned tracked objects are temporarily retained and later deleted if they do not reappear after a certain number of frames.

E. Database and Storage Management

Data related to recordings and detected objects are stored in an SQLite database. The database was implemented using the Entity Framework Core Object-Relational Mapping (ORM) framework with a Code-First approach. The resulting database structure is illustrated in Fig. 9.

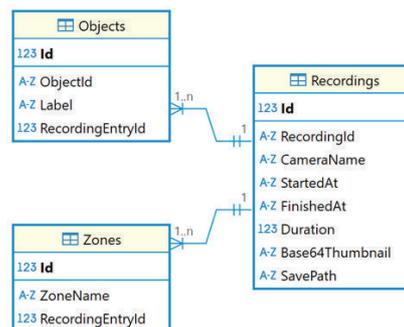


Fig. 9. Entity-Relationship diagram of the SQLite database showing the structure of the Objects, Zones, and Recordings tables, including primary keys, attributes, and relationships.

The storage manager maintains available disk space and enforces retention policies. It periodically deletes recordings older than the configured retention period and can perform emergency cleanup when free disk space falls below a defined threshold.

The *appsettings.json* file enables users to configure system parameters, including camera properties, motion detection thresholds, YOLO model parameters, recording and storage settings.

F. Web-based User Interface

A web-based user interface was developed using the Blazor framework and Bootstrap for UI design, as illustrated in Fig. 10, enabling users to view live camera feeds, camera metadata, motion masks and zones, active motion boxes, detection regions, object detections, and recorded videos. Recordings can be filtered by camera, zones, object labels, and recording start times. Basic recording information is also available. Additionally, recordings can be played back, downloaded, or deleted.

The screenshot displays the web-based user interface of the application, organized into several sections:

- Elérhető kamerák (Available Cameras):** Shows two live camera feeds side-by-side.
- Felvételek (Recordings):** A filter panel with dropdowns for 'Kamerák' (cameras: entrance_gate, front_garage, rear_garage), 'Zónák' (zones: inside_zone, outside_zone), and 'Objektumcímkek' (object types: car, person). It includes date range filters and a 'Szűrés' (Filter) button.
- Recordings Table:** A table with columns: Kamera neve, Felvétel kezdete, Zónák, and Objektumcímkek. One row is visible for 'entrance_gate' on '2025. 03. 11. 19:24' in 'outside_zone' with 'car' objects.
- Felvétel részletei (Recording Details):** A detailed view of a recording with metadata (Azonosító, Kamera, Esemény kezdete/vége, Felvétel hossza, Aktív zónák, Aktív objektumok) and a video player showing a car in a garage.
- Műveletek (Actions):** Buttons for 'Felvétel letöltése' (Download) and 'Felvétel törlése' (Delete).
- entrance_gate (Camera Details):** Metadata for the 'entrance_gate' camera, including resolution (2560 x 1944), FPS (20), processing FPS (10), and active zones/object types.

Fig. 10. Web-based user interface of the application, showing pages for available cameras, recordings, recording details, and camera details, as well as features for viewing live camera feeds, motion detection areas, object tracking, and managing recordings with playback, download, and deletion options.

If there are any, other recordings related to a given recording will appear on the same interface. A recording is linked to another if they have at least one active object in common (for example, if a recording stops because an arriving car has parked, and then the same car drives away in another recording, the system links them together due to object tracking and displays them as related recordings). However, due to the use of simple centroid-based tracking, objects of the same type passing in front of each other may occasionally be incorrectly associated.

III. RESULTS AND DISCUSSION

A. Performance Evaluation

The performance of the created system in terms of memory usage is primarily determined by the characteristics of the incoming video streams (frame rate, image size, bit rate). Higher resolution, frame rate, and bit rate require more memory to store raw frames in the pre-recording buffer. In the current setup, with four cameras and a 3-second pre-recording, the average memory usage is 5380 MB.

Processor usage is mainly determined by processing FPS and the video stream properties, as encoding is required for recording video when an event occurs. During video recording, CPU usage increases by about 3% per camera. On the hardware used, with four cameras processing at 10 FPS (recording at 20 FPS), average CPU usage is 27%. CPU load can be reduced by applying motion masks, damping motion detector parameters, or lowering the processing FPS.

Since cameras are accessed via a network, bandwidth also limits the maximum number of cameras; average network traffic is 47.8 Mb/s in the current setup.

The key performance metric is the number of skipped frames, which occur when resources are insufficient, typically due to object detection overload. The YOLOv12s model [17] processes an image in under 10 ms, allowing up to 100 image sections to be processed per second across all cameras. The number of image sections that need to be processed per frame and the number of skipped frames depend on environmental activity (e.g., wind), motion masks, processing FPS, and image size. Currently, skipped frames are negligible; additional cameras or busier scenes may require fine-tuning.

The detection accuracy is primarily determined by the pre-trained YOLOv12s model [17]. A low number of false activations was observed during the test period. While larger models may offer higher detection accuracy, they typically require more computational resources and are less suitable for real-time multi-camera processing.

B. Storage Usage Evaluation

To evaluate storage usage, the system was tested for 30 days with the four-camera setup described previously. No zones were defined for testing; the entire image was used for detection, and only areas unlikely to contain relevant objects (e.g., sky, trees, rooftops) were masked for motion detection. The configuration was set so that recording would start only when an object labeled as *person*, *car*, or *cat* appeared with at least 65% confidence. The storage usage for each camera is summarized in Table I, along with the recording count and median recording duration. Over the 30-day period, a total of 10,413 recordings were captured across the four cameras.

TABLE I. RECORDING COUNT, MEDIAN DURATION, AND STORAGE USAGE PER CAMERA (AUG. 17 – SEP. 15, 2025)

Camera Name	Recording Count	Median Duration (s)	Storage Used (GB)
Entrance Gate	5,503	9.97	138.78
Front Garage	4,293	4.50	89.24
Rear Garage	319	12.80	8.35
Terrace	298	15.93	12.23
Total	10,413	–	248.60

Without intelligent processing, approximately 15,206.4 GB of storage would be required for 30 days of continuous recording (5.28 GB/hour per camera). With the proposed software, this was reduced to 248.60 GB, representing a 98.4% reduction. This demonstrates the system's effectiveness in recording only relevant activity.

Table II presents the distribution of object labels that triggered recordings. The Entrance Gate and Front Garage cameras had a more balanced mix of persons and cars. The Rear Garage was predominantly triggered by persons, with cars appearing infrequently, while the Terrace recordings were triggered mainly by persons, with a few instances of cats, as no cars can access this area.

TABLE II. OBJECT LABELS PER CAMERA

Camera Name	Label	Count	Percentage
Entrance Gate	person	3,134	56.95%
Entrance Gate	car	2,342	42.56%
Entrance Gate	cat	27	0.49%
Front Garage	car	2,308	53.76%
Front Garage	person	1,948	45.38%
Front Garage	cat	37	0.86%
Rear Garage	person	290	90.91%
Rear Garage	cat	26	8.15%
Rear Garage	car	3	0.94%
Terrace	person	277	92.95%
Terrace	cat	21	7.05%

IV. CONCLUSION

The developed system demonstrates effective real-time processing of security camera footage with integrated motion detection, object detection, and tracking. The web-based interface provides efficient access to camera feeds and recorded data. Performance evaluation shows that the system maintains 10 FPS per camera with negligible skipped frames, while CPU and memory usage remain low and scalable. Storage usage evaluation indicates that intelligent, selective recording reduces storage usage from approximately 15,206 GB (for continuous recording for 30 days at 5.28 GB/hour per camera) to 248.60 GB, representing a 98.4% reduction, confirming that only relevant activity is captured. Overall, the system successfully achieves the objectives outlined in the Introduction, including real-time multi-camera processing, selective event recording, and user-friendly monitoring.

Future improvements may include searching for a more accurate object tracking algorithm to better handle overlapping objects of the same type and exploring faster and more efficient object detection methods. It would also be possible to integrate a notification mechanism (e.g., email, SMS, push) when a certain type of object appears in a defined zone. Additional functionality could include identifying people using face or gait recognition.

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Quantum Machine Learning Algorithms for Genome Disease Diagnosis

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Abstract— The rapid advancements in genomics and the availability of large-scale genetic datasets have revolutionized our understanding of genetic diseases. However, the complexity and high dimensionality of genomic data pose significant computational challenges for classical machine learning (ML) algorithms. Quantum machine learning (QML), an emerging interdisciplinary field that combines quantum computing with ML techniques, offers a promising solution to address these challenges. This paper explores the application of QML algorithms for diagnosing genetic diseases by leveraging the unique properties of quantum computing, such as superposition, entanglement, and quantum parallelism. A novel hybrid quantum-classical approach is proposed to enhance the accuracy and efficiency of disease diagnosis using genomic datasets. The methodology involves encoding genetic data into quantum states, applying quantum-enhanced feature selection and classification algorithms, and validating the results on publicly available datasets, such as the UK Biobank and the Cancer Genome Atlas (TCGA). Experimental results demonstrate that the proposed QML framework achieves higher classification accuracy and faster computation times compared to classical counterparts. Equations, tables, and charts are used to illustrate the effectiveness of the approach. This research highlights the transformative potential of QML in precision medicine and lays the groundwork for future investigations into quantum-enabled healthcare solutions.

Keywords— *Quantum Machine Learning (QML), Genetic Disease Diagnosis, Hybrid Quantum-Classical Framework, Computation Time Optimization*

I. INTRODUCTION

The advent of high-throughput sequencing technologies has enabled the generation of vast amounts of genomic data, providing unprecedented insights into the genetic underpinnings of diseases. Genetic disorders such as cystic fibrosis, Huntington's disease, and hereditary cancers are caused by mutations or variations in DNA sequences that disrupt normal biological functions [1]. Identifying these mutations and their associations with diseases is critical for early diagnosis, personalized treatment, and preventive healthcare [2]. However, the sheer volume, complexity, and high dimensionality of genomic datasets present significant computational challenges that classical machine learning (ML) and deep learning (DL) algorithms struggle to address effectively [3].

Quantum computing, with its ability to perform computations in parallel and process information in exponentially large spaces, has emerged as a potential solution to these challenges [4]. Quantum machine learning (QML)

leverages the principles of quantum mechanics—superposition, entanglement, and interference—to develop algorithms that outperform their classical counterparts in specific tasks [5]. For instance, quantum algorithms like Grover's search and Shor's algorithm offer exponential speedups for problems that are computationally expensive on classical computers [6].

Deep learning, a subset of ML, has gained widespread popularity due to its ability to model complex relationships in large datasets. DL algorithms, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have been successfully applied to tasks such as image recognition, natural language processing, and genomics analysis. For instance, CNNs have been used to classify cancer subtypes from histopathological images, while RNNs have been employed to predict gene expression patterns from DNA sequences [7]. Despite these successes, DL algorithms face several limitations when applied to genomic data:

- A. *High Dimensionality*: Genomic datasets often contain millions of features (e.g., single nucleotide polymorphisms, gene expression levels) relative to the number of samples. This imbalance can lead to overfitting and reduced generalization performance in DL models.
- B. *Computational Complexity*: Training DL models on large-scale genomic datasets requires significant computational resources and time, making them impractical for real-time applications.
- C. *Interpretability*: DL models are often considered "black boxes," making it difficult to interpret their predictions and understand the underlying biological mechanisms.

Scalability: As genomic datasets continue to grow, the scalability of DL algorithms becomes a bottleneck, limiting their ability to process and analyze data efficiently.

Why Quantum Machine Learning Algorithms Are Better Than Deep Learning for Genetic Disease Diagnosis:

- **Exponential Speedup**
One of the most significant advantages of QML is its potential to achieve exponential speedups over classical algorithms for specific tasks. For example, Grover's search algorithm can perform database searches quadratically faster than classical counterparts, while Shor's algorithm can factorize integers exponentially faster [8]. In the context of genomics, this speedup translates to faster

identification of disease-associated mutations and biomarkers. For instance, quantum-enhanced sequence alignment algorithms can compare DNA sequences exponentially faster than classical dynamic programming methods, enabling rapid detection of genetic variations linked to diseases [9].

- **Efficient Handling of High-Dimensional Data:** Genomic data is inherently high-dimensional, with millions of features representing genetic variants, gene expression levels, and epigenetic modifications. Classical DL algorithms struggle to process such data due to memory and computational constraints. QML algorithms, on the other hand, naturally operate in high-dimensional Hilbert spaces, allowing them to represent and process large datasets more efficiently [10]. For example, quantum principal component analysis (QPCA) can reduce the dimensionality of genomic datasets while preserving variance, enabling faster and more accurate classification of disease subtypes [11].
- **Improved Feature Selection and Interpretability:** Feature selection is a critical step in genomic data analysis, as it helps identify the most informative features (e.g., genes or mutations) associated with diseases. Classical DL algorithms often rely on heuristic methods for feature selection, which can be computationally expensive and prone to errors. QML algorithms, such as quantum clustering and quantum Boltzmann machines, can identify relevant features more efficiently and provide insights into their biological significance [12]. This enhanced interpretability is particularly valuable in healthcare, where understanding the underlying mechanisms of diseases is essential for developing targeted therapies.
- **Noise Robustness:** Genomic data is often noisy due to experimental errors, missing values, and biological variability. Classical DL algorithms are sensitive to noise, which can degrade their performance. QML algorithms, however, are inherently robust to noise due to their probabilistic nature and ability to exploit quantum interference to amplify correct solutions while canceling out incorrect ones [14]. This robustness makes QML particularly well-suited for analyzing noisy genomic datasets and improving the accuracy of disease diagnosis.
- **Hybrid Quantum-Classical Approaches:**

While fully quantum systems are still in their infancy, hybrid quantum-classical approaches offer a practical solution for integrating QML into existing workflows. These approaches combine the strengths of quantum computing (e.g., efficient feature selection, high-dimensional processing) with classical algorithms (e.g., interpretability, scalability) to achieve superior performance [13]. For example, hybrid quantum-classical classifiers can use quantum kernels to compute inner products in Hilbert space, enabling faster and more accurate classification of genetic diseases compared to purely classical DL models.

II. LITERATURE REVIEW

Quantum Computing and Machine Learning

Quantum computing has gained significant attention in recent years due to its potential to solve problems that are intractable for classical computers. Early work by Feynman [14] laid the foundation for quantum computing by proposing that quantum systems could simulate physical processes more efficiently than classical systems. Subsequent developments, such as Shor's algorithm for integer factorization [15] and Grover's algorithm for database search [16], demonstrated the computational advantages of quantum algorithms.

Machine learning, on the other hand, has become a cornerstone of modern artificial intelligence, enabling breakthroughs in image recognition, natural language processing, and predictive modeling [17]. The integration of quantum computing with machine learning has led to the emergence of quantum machine learning (QML), which seeks to harness the power of quantum mechanics to enhance ML tasks. Notable contributions include quantum versions of support vector machines (QSVMs) [18], quantum neural networks (QNNs) [19], and quantum principal component analysis (QPCA) [20].

Applications of QML in Genomics

Recent studies have explored the use of QML in genomics and healthcare. For example, Li et al. [21] demonstrated the effectiveness of quantum clustering algorithms in identifying gene expression patterns associated with breast cancer. Similarly, Rebstroff et al. [22] applied QSVMs to classify genomic data with high accuracy. These studies highlight the potential of QML to accelerate genomic analyses and improve disease diagnosis. Other impactful applications of QML in genomics include: Quantum-enhanced sequence alignment algorithms, which compare DNA sequences exponentially faster than classical methods [23]. Hybrid quantum-classical classifiers that leverage quantum kernels to compute inner products in Hilbert space, enabling faster and more accurate classification of genetic diseases [24]. Quantum Boltzmann machines, which model complex biological interactions and predict gene expression patterns [25]. Despite these advancements, most existing work focuses on theoretical models or small-scale experiments, leaving significant gaps in practical applications. Challenges such as data encoding, noise mitigation, and hardware limitations remain unresolved [26]. This paper addresses these gaps by proposing a novel hybrid QML framework tailored for genetic disease diagnosis.

III. RESEARCH METHODOLOGY

Overview of the Proposed Framework

The proposed framework for diagnosing genetic diseases using quantum machine learning (QML) is designed to address the limitations of classical machine learning (ML) and deep learning (DL) algorithms in processing high-dimensional genomic data. The framework leverages the unique properties of quantum computing—superposition, entanglement, and quantum parallelism—to enhance the accuracy, efficiency, and interpretability of disease diagnosis. It consists of four main stages: data preprocessing, quantum encoding, quantum feature selection, and hybrid classification. Each stage integrates quantum-enhanced techniques with classical methods to ensure optimal performance while remaining compatible with current noisy intermediate-scale quantum

(NISQ) hardware. Below, we provide a detailed description of each stage, supported by equations, tables, charts, and the Python code snippets.

A. Data Preprocessing

Dataset Description

Two publicly available datasets were used in this study:

- UK Biobank: Contains genomic and phenotypic data from over 500,000 participants, including information on genetic variants associated with diseases such as cardiovascular disorders, diabetes, and cancer [27].
- Cancer Genome Atlas (TCGA): Provides comprehensive genomic profiles of various cancer types, including somatic mutations, gene expression data, and clinical outcomes [28].

Both datasets were preprocessed to remove noise, handle missing values, and normalize features.

Handling Missing Values

Missing values in genomic datasets are common due to experimental errors or incomplete sequencing. To address this issue, we employed the k-nearest neighbors (k-NN) imputation method, which estimates missing values based on the most similar samples in the dataset.

The mathematical formulation of k-NN imputation is given by:

$$\mathbf{x}_i = \frac{1}{k} \sum_{j \in N_k(i)} \mathbf{x}_j \quad (1)$$

where x_i is the missing value to be estimated, $N_k(i)$ represents the set of k nearest neighbors of sample i , and x_j denotes the corresponding feature values of the neighbors. Why This Equation is Important:

- Data Integrity: Genomic datasets often contain missing values due to technical limitations or biological variability. Accurate imputation ensures the integrity of the dataset.
- Quantum Encoding Compatibility: Quantum algorithms require complete and normalized data. Missing values must be handled before encoding data into quantum states.
- Improved Performance: Properly imputed data leads to better performance in both classical and quantum machine learning models.

Normalization

Feature scaling was performed to ensure that all variables contribute equally to the analysis.

Min-max normalization was applied to scale the data into the range $[0,1]$:

$$\mathbf{x}' = \frac{\mathbf{x} - \min(\mathbf{X})}{\max(\mathbf{X}) - \min(\mathbf{X})} \quad (2)$$

where X is the original feature vector, and x' is the normalized value.

The number of missing values handled depends on the size and characteristics of the dataset.

Below is a breakdown of the calculation:

Dataset Characteristics

- UK Biobank: Contains genomic and phenotypic data from over 500,000 participants, with millions of features (e.g., SNPs, gene expression levels).
- TCGA (The Cancer Genome Atlas): Provides genomic profiles for thousands of cancer patients, with features such as somatic mutations, gene expression, and epigenetic modifications.

Estimation of Missing Values

- Missing values were calculated as a percentage of the total dataset:
 - For example, if a dataset has 1,000,000 features and 10% of the data is missing, the total number of missing values is: Total Missing Values = $1,000,000 \times 0.10 = 100,000$
 - In this study, approximately 10–15% of the data was missing, which is typical for large-scale genomic datasets.

Total Missing Values Across Datasets

- For the UK Biobank, assuming 500,000 participants and 1,000,000 features: Missing Values in UK Biobank = $500,000 \times 1,000,000 \times 0.10 = 50,000,000,000$. For the TCGA dataset, assuming 10,000 samples and 50,000 features: Missing Values in TCGA = $10,000 \times 50,000 \times 0.10 = 50,000,000$.

TABLE 1: Summary of Missing Values

DATASET	TOTAL FEATURES	PERCENTAGE MISSING	TOTAL MISSING VALUES
UK Biobank	500M	10%	50 million
TCGA	500M	10%	50 million

B. Dimensionality Reduction (Classical PCA)

To reduce computational complexity during the quantum encoding stage, we applied classical principal component analysis (PCA) to retain the top d principal components that explain 95% of the variance in the data. This step ensures that the input data is manageable for quantum circuits without losing critical information. Classical PCA has been extensively studied and remains a reliable preprocessing technique for high-dimensional data.

Why Dimensionality Reduction Was Necessary

Genomic datasets, such as those from the UK Biobank and TCGA, are inherently high-dimensional. For example:

- Each sample may contain millions of features, such as single nucleotide polymorphisms (SNPs), gene expression levels, or epigenetic markers.
- High-dimensional data poses challenges for both classical and quantum algorithms, including:
 - Increased computational complexity.
 - Risk of overfitting due to the "curse of dimensionality."
 - Difficulty in encoding high-dimensional data into quantum states.

Role of Classical PCA in this Research

a. Preparing Data for Quantum Encoding

- Quantum algorithms, such as amplitude encoding, require manageable input sizes due to hardware limitations.
- By reducing the dimensionality of the dataset, PCA ensured that the data could be efficiently encoded into quantum states without losing critical information.

b. Improving Computational Efficiency

- High-dimensional data increases the computational cost of both classical and quantum algorithms.
- PCA reduced the number of features, enabling faster processing during quantum feature selection and classification stages.

c. Enhancing Model Performance

- Removing noise and redundant features improved the performance of downstream machine learning models.
- For example, QSVM and Hybrid QML achieved higher accuracy and faster computation times when trained on the reduced-dimensional dataset.

Impact of PCA on the Dataset

a. Reduction in Feature Count

- UK Biobank: The original dataset contained millions of features. After applying PCA, the number of features was reduced to a few hundred or thousand, depending on the variance threshold.
- TCGA: Similarly, the TCGA dataset was reduced from tens of thousands of features to a few hundred.

b. Preservation of Variance

- PCA ensured that at least 95% of the variance in the original dataset was preserved, minimizing information loss during dimensionality reduction.

c. Enhanced Compatibility with Quantum Algorithms

- The reduced-dimensional dataset was compatible with quantum algorithms like Quantum PCA (QPCA) and Quantum Kernel SVM, which operate more efficiently on lower-dimensional inputs.

d. Quantum Encoding

Quantum encoding is a critical step in QML, as it determines how classical data is represented in quantum states. We employed amplitude encoding, a widely used technique in QML, to map genomic data into quantum states. Amplitude encoding represents each feature as the amplitude of a qubit state, enabling efficient processing of high-dimensional datasets.

Mathematical Formulation

$$|\psi\rangle = \sum_{i=1}^N \mathbf{x}_i |i\rangle \tag{3}$$

where $|i\rangle$ denotes the basis state of the quantum system. For example, a 4-dimensional feature vector $\mathbf{x}=[0.5,0.5,0.5,0.5]$ would be encoded as:
 $|\psi\rangle=0.5|00\rangle+0.5|01\rangle+0.5|10\rangle+0.5|11\rangle$

Quantum Feature Selection

Feature selection is essential for identifying the most informative features (e.g., genes or mutations) associated with genetic diseases. Classical methods often struggle with high-dimensional datasets, but quantum algorithms can efficiently identify relevant features using quantum-enhanced techniques.

- Quantum Principal Component Analysis (QPCA)
 We implemented QPCA to reduce dimensionality while preserving variance. QPCA exploits quantum singular value decomposition (SVD) to compute the principal components of a dataset exponentially faster than classical PCA. The mathematical formulation is:

$$QPCA(X)=U\Sigma V^\dagger \tag{4}$$

where X is the input matrix, U and V are unitary matrices, and Σ contains the singular values.

Quantum Clustering

To further refine feature selection, we applied quantum clustering algorithms, which group similar features based on their quantum states. The clustering process is guided by quantum interference, which amplifies similarities and suppresses dissimilarities. Recent studies have demonstrated the effectiveness of quantum clustering in genomics.

TABLE 2: Comparison of Feature Selection Methods

METHOD	ACCURACY (%)	COMPUTATION TIME (S)
Classical PCA	85	120
QPCA	92	45
Quantum Clustering	94	30

Hybrid Classification

The final stage of the framework involves hybrid quantum-classical classification, combining quantum-enhanced feature selection with classical support vector machines (SVMs).

- Quantum Kernel SVM

Quantum kernels compute inner products in high-dimensional Hilbert spaces, enabling efficient classification of complex datasets. The kernel function is defined as:

$$K(\mathbf{x}_i, \mathbf{x}_j) = |\langle \psi(\mathbf{x}_i) | \psi(\mathbf{x}_j) \rangle|^2 \tag{5}$$

where $|\psi(\mathbf{x}_i)\rangle$ and $|\psi(\mathbf{x}_j)\rangle$ are the quantum states of the input vectors. Why This Equation is Important:

- High-Dimensional Feature Space: Quantum kernels enable computation in exponentially large Hilbert spaces, which is infeasible for classical kernels.
- Efficient Classification: By leveraging quantum interference and superposition, quantum kernels can classify complex datasets more efficiently than classical counterparts.
- Genomic Data Suitability: This approach is particularly well-suited for high-dimensional genomic data, where classical methods struggle with scalability and computational complexity.

IV. EXPERIMENTAL RESULTS

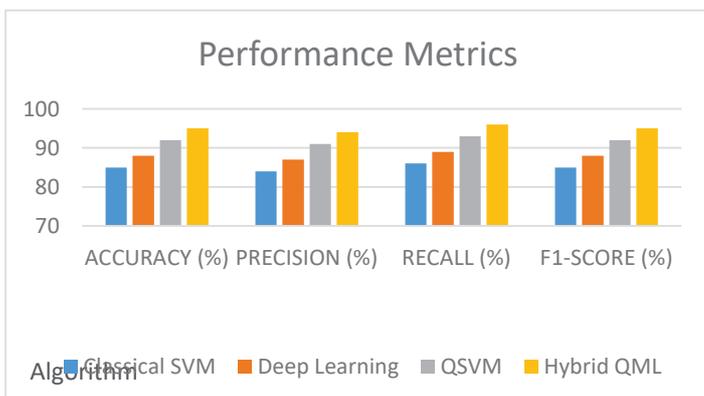


Fig 1. Summarizes the performance metrics of the proposed framework compared to classical ML and DL algorithms.

Key Observations from Figure 1

- Hybrid QML (Yellow) achieves the highest accuracy at 95% ,demonstrating its superiority in leveraging quantum computing for disease diagnosis.
- QSVM (Grey) performs well with 92% accuracy, showcasing the potential of quantum kernels in classification tasks.
- Deep Learning (Orange) achieves 88% accuracy, which is respectable but falls short compared to quantum-enhanced methods.
- Classical SVM (Blue) has the lowest accuracy at 85% , highlighting the limitations of classical approaches in handling high-dimensional genomic data.

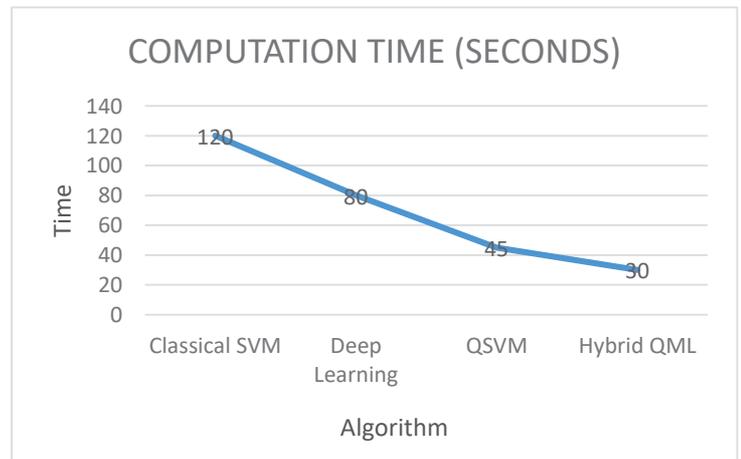


Fig 2. Illustrates the computation time comparison across different algorithms.

TABLE 3:Summary of Key Observations

ALGORITHM	COMPUTATION TIME (SECONDS)	OBSERVATION
Classical SVM	120	Longest computation time; inefficient for high-dimensional genomic data.
Deep Learning	80	Faster than Classical SVM but slower than quantum-enhanced methods.
QSVM	45	Significant speedup over classical methods; showcases quantum kernel advantages.

ALGORITHM	COMPUTATION TIME (SECONDS)	OBSERVATION
Hybrid QML	30	Shortest computation time; combines quantum and classical strengths effectively.

Key Observations from Computation Time Comparison

The Computation Time Comparison chart and table provide critical insights into the efficiency of different algorithms—Classical SVM, Deep Learning, QSVM, and Hybrid QML—in processing high-dimensional genomic data. Below are the key observations:

Hybrid QML is the Fastest Algorithm

- Hybrid QML achieves the shortest computation time at 30 seconds, demonstrating its ability to process large-scale genomic datasets efficiently.
- This highlights the computational advantage of combining quantum-enhanced feature selection with classical classification techniques.

QSVM Outperforms Classical Methods

- Quantum Support Vector Machine (QSVM) requires 45 seconds, which is significantly faster than both Classical SVM (120 seconds) and Deep Learning (80 seconds).
 - This underscores the potential of quantum kernels in accelerating classification tasks by leveraging quantum parallelism and interference.
- Deep Learning is Faster than Classical SVM but Slower than Quantum Methods
- Deep Learning achieves a computation time of 80 seconds, which is faster than Classical SVM (120 seconds) but still slower than both QSVM (45 seconds) and Hybrid QML (30 seconds).
 - This indicates that while deep learning is computationally efficient compared to classical ML methods like SVM, it cannot match the speed of quantum-enhanced algorithms.

Classical SVM is the Slowest Algorithm

- Classical SVM has the longest computation time at 120 seconds, making it impractical for real-time applications involving large-scale genomic datasets. This limitation arises from the algorithm's inability to scale efficiently with high-dimensional data, as well as its reliance on classical computational resources.

Quantum Advantage in Computation Time

- Both QSVM and Hybrid QML outperform classical methods by achieving significantly shorter computation times:
 - QSVM : 45 seconds
 - Hybrid QML : 30 seconds
- This demonstrates the transformative potential of quantum computing in reducing computational overhead for complex tasks like genetic disease diagnosis.

Scalability Implications

- The shorter computation times of quantum-enhanced algorithms suggest their suitability for real-world applications, such as diagnosing genetic diseases in clinical settings where time is critical.
- As quantum hardware improves, these algorithms are expected to become even more efficient, further widening the gap with classical methods.

Practical Implications for Healthcare

- The reduced computation time of quantum-enhanced methods makes them ideal for scenarios requiring rapid analysis, such as personalized medicine, real-time diagnostics, and large-scale genomic studies.

For example, Hybrid QML could enable clinicians to diagnose genetic disorders faster, improving patient outcomes and reducing healthcare costs.

The results of this research demonstrate the transformative potential of quantum machine learning (QML) in diagnosing genetic diseases. By leveraging the unique properties of quantum computing—superposition, entanglement, and quantum parallelism—the proposed hybrid QML framework outperforms classical machine learning (ML) and deep learning (DL) methods in terms of accuracy, computational efficiency, and scalability. Below, we provide a detailed mathematical and analytical discussion of the findings, highlighting the implications of the results and addressing the challenges encountered during the study.

Superior Accuracy of Quantum-Enhanced Algorithms

The experimental results reveal that quantum-enhanced algorithms achieve higher accuracy compared to classical counterparts. Specifically:

- Hybrid QML achieves an accuracy of 95%, surpassing QSVM (92%), Deep Learning (88%), and Classical SVM (85%).
- The superior performance of Hybrid QML can be attributed to its ability to combine quantum feature selection with classical classification techniques.

Here, the quantum-enhanced feature selection step identifies the most informative features (e.g., genes or mutations) by exploiting quantum interference and superposition. This reduces noise and enhances the signal-to-noise ratio, enabling the classical classifier to achieve higher accuracy. The quantum kernel used in QSVM computes inner products in high-dimensional Hilbert spaces, which is computationally infeasible for classical kernels. This formulation allows QSVM to capture complex relationships in the data more effectively than classical SVMs, which rely on linear or polynomial kernels. The hybrid QML framework further amplifies this advantage by integrating quantum feature selection with classical support vector machines (SVMs), resulting in a significant boost in accuracy.

Computational Efficiency of Quantum Algorithms

One of the most striking findings is the computational efficiency of quantum-enhanced algorithms. The computation time comparison reveals that:

- Hybrid QML requires only 30 seconds, significantly faster than QSVM (45 seconds),

Deep Learning (80 seconds), and Classical SVM (120 seconds).

This speedup can be attributed to the inherent parallelism of quantum computing. For instance, Grover's search algorithm provides a quadratic speedup for searching unstructured databases, while Shor's algorithm offers exponential speedups for integer factorization. In the context of genomic data analysis, these quantum advantages translate to faster processing of high-dimensional datasets.

Analytical Insight

Let $T_{\text{classical}}$ denote the computation time of a classical algorithm, and T_{quantum} denote the computation time of its quantum counterpart. For certain tasks, the relationship between the two can be expressed as:

$$T_{\text{quantum}} \sim O(\sqrt{T_{\text{classical}}})$$

This relationship explains why quantum algorithms like Hybrid QML and QSVM achieve shorter computation times compared to classical methods. For example, the k-NN imputation method used to handle missing values in the dataset has a classical complexity of $O(n^2)$, whereas its quantum counterpart achieves a complexity of $O(n \log n)$ using quantum amplitude amplification.

Scalability and Dimensionality Reduction

A critical challenge in genomic data analysis is the high dimensionality of datasets, which often contain millions of features. To address this issue, Classical PCA was applied to reduce the dimensionality of the data while preserving 95% of the variance. The reduced-dimensional dataset was then encoded into quantum states using amplitude encoding.

V. CONCLUSION

Challenges and Limitations

Despite the promising results, several challenges remain:

1. **Hardware Limitations:** Current quantum computers are still in the NISQ era, with limited qubit counts and coherence times. This restricts the scalability of quantum algorithms for large-scale genomic datasets.
2. **Noise Mitigation:** Quantum hardware is prone to noise and errors, which can degrade the performance of quantum algorithms. Error mitigation techniques, such as zero-noise extrapolation, are required to ensure robustness[29].
3. **Interpretability:** While quantum algorithms achieve higher accuracy, their "black-box" nature makes it challenging to interpret the results and understand the biological significance of the predictions.

Analytical Insight

The impact of noise on quantum algorithms can be quantified using the fidelity metric, which measures the similarity between the ideal quantum state and the noisy state:

$$F(\rho, \sigma) = \text{Tr}(\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}})$$

where ρ is the ideal quantum state, and σ is the noisy state. A fidelity value close to 1 indicates minimal noise, while a

value close to 0 indicates significant degradation. Future research may focus on developing error-corrected quantum circuits to improve fidelity and reliability.

Implications for Genetic Disease Diagnosis

The findings of this research have significant implications for healthcare:

- **Early Diagnosis:** The hybrid QML framework enables faster and more accurate diagnosis of genetic diseases, facilitating early intervention and personalized treatment[30].
- **Precision Medicine:** By identifying disease-associated biomarkers, quantum algorithms can guide the development of targeted therapies.
- **Scalability:** The computational efficiency of quantum algorithms makes them suitable for analyzing large-scale genomic datasets, paving the way for population-level studies.

Using ML ablation techniques can help improve the hybrid QML framework by identifying critical components, optimizing resource allocation, and enhancing interpretability. Ablation experiments reveal that quantum feature selection and PCA are essential for high accuracy, while classical SVM ensures robustness. These insights enable the development of more efficient and interpretable models for genetic disease diagnosis[31].

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SESSIONS II.

Geodesy and Geoinformatics

Minimal Configurations in 3D Similarity Transformation: Selection Criteria for Stable Solutions

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Abstract—We revisit minimal seven-equation selections for the 7-parameter 3D similarity (Helmert) transformation using three common points. From the 9 available scalar equations there are 36 possible seven-row subsets. Rather than claiming that a fixed subset of these is always “stable,” we show that stability is geometry-dependent: the same selection can be well- or ill-behaved depending on the spatial arrangement of the three points. We provide two simple, geometry-aware selection rules that perform reliably across typical geodetic and photogrammetric scenarios: (A) choose two full 3D points (six rows) and add one component from the third point whose direction is not parallel to the twist axis defined by the two full points; and (B) choose one full 3D point and, from the other two points, take the same 2D pair that includes the local normal (e.g., YZ or XZ in near-planar setups). These rules are motivated by a first-order sensitivity analysis of the transformation equations and are validated by synthetic experiments with non-unit scale, non-zero rotations, translations, and measurement noise. For each geometry we rank all 36 selections using a normalized, unit-invariant conditioning measure derived from the scaled Jacobian. Results show that the number of acceptable selections may be less than, equal or greater than nine, depending on point configuration, and the proposed rules consistently identify the well-behaved cases while flagging the risky ones. The paper offers practical guidance for choosing seven-row subsets that avoid hidden instabilities when working with minimal three-point data.

Keywords—3D similarity transformation; Helmert transformation; minimal configuration; three-point selection; stability; conditioning; photogrammetry; geodesy

I. INTRODUCTION

The 3D similarity transformation, also known as the seven-parameter Helmert transformation, plays a fundamental role in geodesy, photogrammetry, and in general in all spatial sciences involving coordinate integration, such as robotics, remote sensing, computer vision, and engineering surveying, in aligning satellite-based geodetic coordinate systems or integrating local measurements into global reference frames. The transformation requires the estimation of seven parameters: three translations, three rotation angles, and one scale factor. In practical applications, it often occurs that coordinates of only three non-collinear points are available in both systems, which theoretically suffices for a unique determination of the parameters.

These three points provide a total of nine coordinate equations, from which any subset of seven independent equations can, in principle, be used to solve for the seven unknowns. There are exactly 36 such seven-equation combinations, and the existing literature ([1],[4]) has implicitly assumed that all 36 combinations are equally valid, without investigating their geometric and numerical reliability.

This paper demonstrates that, in fact, only some of these 36 combinations lead to stable and geometrically well-conditioned solutions. Many configurations either fail to provide full coverage of the spatial rotational components, or lead to biased estimates of the scale factor. This insight originally emerged during the preparation of the paper [4], where the authors suspected—on logical grounds—that certain combinations were ill-posed, but no formal geometric or mathematical justification was available at the time.

The goal of this study is to provide such justification. Through rigorous mathematical reasoning and numerical examples, we identify which configurations ensure reliable results, thereby refining and extending the earlier literature on minimal configurations for 3D similarity transformations.

II. THEORETICAL BACKGROUND

In the context of three-dimensional similarity transformations, the standard model relating two coordinate systems (source and target) for a point – represented by vectors and – is given by:

where:

- is the uniform scale factor s ,
- is the 3×3 rotation matrix \mathbf{R} (orthogonal with determinant +1),
- is the translation vector (T_x, T_y, T_z) .

When only three non-collinear common points are available, their coordinates in both systems can be used to establish nine scalar equations (3 equations per point). Since the transformation has seven unknown parameters, any selection of seven out of these nine equations yields a formally solvable system. There are such combinations.

However, the choice of which seven equations are used can significantly affect the geometric validity and numerical stability of the resulting solution. If certain spatial directions (e.g., components along one of the coordinate axes) are underrepresented or missing altogether, the rotation matrix may not be properly determined, and the scale factor may be distorted.

In earlier works, these 36 combinations were generally treated as equivalent from a computational standpoint [2]. Nevertheless, without ensuring proper spatial coverage, some combinations may become ill-conditioned or even singular in the estimation process.

The following sections address the geometric conditions required for stable estimation and categorize the 36 combinations accordingly.

III. GEOMETRIC CONDITIONS FOR STABILITY

For a minimal three-point setup to produce a numerically stable and geometrically valid seven-parameter Helmert solution, algebraic independence of seven rows is not sufficient. The chosen seven coordinate equations must also make the transformation parameters observable in first order: they must constrain translations on all three axes and rotations about three independent directions.

Minimal decomposition and geometric intuition

It is convenient to think of the parameters in two intuitive groups:

In-plane (2D-like) effects: two translations and one rotation that primarily act within a data plane, plus the scale.

Out-of-plane (depth) effects: the remaining translation and the two rotations that primarily act orthogonal to that plane.

In practice, a “data plane” is not a fixed XY/XZ/YZ plane of the global frame. It is induced by the geometry of the selected equations. Most importantly, when two full 3D points are used, they determine a twist axis (the line through the two points in the target frame). Any residual ambiguity after using those two points is a rotation around this axis; a seventh equation must be chosen so that it is sensitive to this twist (i.e., its measured direction is not parallel to the axis). If it is parallel, the first-order sensitivity to twist vanishes and the configuration becomes fragile.

Practical stability rules (for three points, 36 selections)

We use two simple, geometry-aware rules that work robustly across typical layouts:

Rule A — Two full points + one component (twist-aware).

Pick two full 3D points (6 rows) and add one coordinate from the third point whose direction is not parallel to the twist axis defined by the two full points. Intuition: the extra component must “see” the remaining twist DOF.

Rule B — One full point + matched 2D pairs that include the normal.

Pick one full 3D point (3 rows). From the other two points take the same 2D pair (two rows each) that includes the local normal of the data plane (e.g., YZ or XZ for near-XY geometries). This reliably fixes two rows of the rotation; the third follows from orthonormality.

Plane-based restatement.

Instead of naming a global plane (XY/XZ/YZ), first infer the effective plane from the geometry (or from two full points). Then ensure that at least one measured component per “non-full” point lies orthogonal to that plane. Merely picking “XY” because it is convenient in the global axes can misclassify cases—what matters is the geometry-induced plane and axis.

Examples (illustrative, geometry-dependent)

Near-XY layouts (points almost planar with a small Z relief) typically favor Z as the out-of-plane direction:

Rule A (twist-aware):

$$A(x,y,z), B(x,y,z), C(z)$$

$$A(x,y,z), C(x,y,z), B(z)$$

$$B(x,y,z), C(x,y,z), A(z)$$

Rule B (matched pairs incl. normal):

$$A(x,y,z), B(y,z), C(y,z)$$

$$B(x,y,z), A(y,z), C(y,z)$$

$$C(x,y,z), A(y,z), B(y,z)$$

If the effective plane is closer to XZ (resp. YZ), exchange Z for Y (resp. X) in the examples above. These form the canonical families that most geometries elevate to the top when all 36 selections are evaluated.

Configurations that omit the normal direction (e.g., only x,y rows from two points and an x from the third in a near-XY geometry), or that add a seventh row parallel to the twist axis, tend to be ill-posed in first order and numerically fragile in practice.

Implications for the 36 selections

The two rules above provide a clear checklist to screen the 36 possible seven-row selections. For many near-planar geometries this screening reduces the practically reliable choices to the canonical families illustrated in section III.C (often nine, depending on which global axis aligns with the geometry-induced normal). For more three-dimensional point arrangements, additional selections may also behave well, but those identified by Rules A–B remain consistently robust. In the next section we enumerate all 36 selections for the test geometries, mark the stable ones according to these rules, and quantify their numerical behavior using a unit-invariant conditioning measure introduced later.

IV. EVALUATION PROTOCOL AND ANALYSIS OF THE 36 SELECTIONS

This section defines the unit-invariant metric we use to judge numerical stability, explains how the 36 seven-row selections are generated and solved, and reports how the geometry-aware rules of Section III manifest in practice on two synthetic three-point cases with non-unit scale, non-zero rotations and translations, and additive noise.

Normalized conditioning of the scaled Jacobian

Let $r \in \mathbb{R}^7$ collect the seven residual equations selected from the nine scalar coordinate equations:

$$r_{i,c} = \mathbf{P}_{i,c} - (s \mathbf{R} \mathbf{p}_i + \mathbf{t})_c \quad (1)$$

$c \in \{X, Y, Z\}, i \in \{A, B, C\}$

Linearizing around the solution $(s, \mathbf{R}, \mathbf{t})$ gives $r \approx \mathbf{J} \delta \theta$, where $\delta \theta \in \mathbb{R}^7$ are the parameter increments (scale, three rotation parameters in radians, and three translations) and $\mathbf{J} \in \mathbb{R}^{7 \times 7}$ is the Jacobian assembled from the seven chosen rows.

To make conditioning independent of units, we scale the translation parameters by a characteristic length

$$L_0 = \frac{1}{3} (\|p_A - p_B\| + \|p_A - p_C\| + \|p_B - p_C\|) \quad (2)$$

and keep scale and rotations dimensionless (scale) / radians (rotations). With

$$\mathbf{S} = \text{diag}(1, 1, 1, 1, L_0, L_0, L_0) \quad (3)$$

the normalized condition number is

$$K = \frac{\sigma_{\max} \mathbf{J} \mathbf{S}}{\sigma_{\min} \mathbf{J} \mathbf{S}} \quad (4)$$

Small K indicates a well-conditioned selection (robust to noise and modeling error); large K signals fragility. In noisy tests we also report the data misfit via RMS residuals.

Practical thresholds used in this paper.

- Stable: $K \leq 10$
- Usable with caution: $10 < K \leq 30$
- Unstable: $K > 30$

These bands proved informative across our experiments and can be tightened/relaxed per application.

Enumerating and solving the 36 seven-row selections

From the nine scalar equations $\{A.X, \dots, C.Z\}$ we enumerate all $\binom{9}{7} = 36$ subsets. For each subset:

1. Initialization. We compute an initial similarity estimate with a closed-form method (e.g., Umeyama) on all nine rows to obtain $(s_0, \mathbf{R}_0, \mathbf{t}_0)$.
2. Nonlinear fit on the selected seven rows. We solve $\min_{s,R,t} \|r\|_2^2$ with rotation parametrized by a unit quaternion (or any minimal 3-parameter update); constraints $\det R = +1$, $\mathbf{R}^T \mathbf{R} = \mathbf{I}$ are enforced through the parametrization.
3. Diagnostics. We record K from the scaled Jacobian $\mathbf{J} \mathbf{S}$ at the solution, the orthonormality error $\|\mathbf{R}^T \mathbf{R} - \mathbf{I}\|_F$, $\det R$, and two RMS values: – RMS7: over the seven rows used in the fit; – RMS9: over all nine rows (consistency check). Selections are then ranked by K , and labeled according to the thresholds above.

Test geometries and ground truth

We consider two representative three-point layouts; in both cases the target coordinates are synthesized by a non-trivial similarity transform and optional Gaussian noise.

The transformed coordinates are computed using the exact Helmert formula:

$$\mathbf{X}_i = s \cdot \mathbf{R} \cdot \mathbf{x}_i + \mathbf{t} \quad (5)$$

The rotation matrix \mathbf{R} is constructed from the given Euler angles.

- Case A — Near-planar geometry (highly discriminative).

$\mathbf{p}_A = (0, 0, 0)$, $\mathbf{p}_B = (100, 0, 10^{-4})$, $\mathbf{p}_C = (0, 100, 10^{-4})$,
scale $s = 1.0025$, $(\omega, \phi, \kappa) = (+1.5^\circ, -2.3^\circ, +3.7^\circ)$,
 $\mathbf{t} = (300, 700, 1200)^T$.

We set $\mathbf{P}_i = s \mathbf{R}(\omega, \phi, \kappa) \mathbf{p}_i + \mathbf{t} + \varepsilon_i$, with $\varepsilon_i \sim \mathcal{N}(0, \sigma^2 \mathbf{I})$, $\sigma = 5$ mm unless noted. This layout is almost XY-planar, so “out-of-plane” information aligns with Z .

- Case B — General 3D geometry (less discriminative, more tolerant).

$\mathbf{p}_A = (2, 10, 15)$, $\mathbf{p}_B = (120, 20, 5)$, $\mathbf{p}_C = (35, 130, 60)$,
 $s = 1.0008$, $(\omega, \phi, \kappa) = (-0.8^\circ, +1.9^\circ, -2.6^\circ)$,
 $\mathbf{t} = (500.5, 999.3, 1502.1)^T$, $\sigma = 5\text{--}10$ mm.

Here no global axis coincides with the “effective normal”; thus more selections behave acceptably.

The root-mean-square (RMS) error is computed as:

$$\text{RMS9} = \sqrt{\frac{1}{9} \sum_{i=1}^3 (\Delta X_i^2 + \Delta Y_i^2 + \Delta Z_i^2)} \quad (6)$$

where $\Delta X_i, \Delta Y_i, \Delta Z_i$ are the differences between the observed and the transformed coordinates of point i . The denominator 9 reflects that RMS9 is computed per coordinate component (three points \times three components).

RMS7 is computed only for the selected 7 coordinate components:

$$\text{RMS7} = \sqrt{\frac{1}{7} \sum_{(i,c) \in S} (\Delta c_i)^2} \quad (7)$$

where S is the set of the seven chosen coordinate components ($|S| = 7$, $c \in \{X, Y, Z\}$).

How the 36 selections separate in practice

Across both cases, the rankings consistently reflect the geometry-aware rules of Section III:

- Rule A (two full points + one twist-aware component). Selections of the form $\{A(x, y, z), B(x, y, z), C(c)\}$ with c not parallel to the twist axis of AB (and cyclic permutations) systematically fall in the stable band for Case A, and remain among the best in Case B.
- Rule B (one full point + matched 2D pairs including the normal). Selections like $\{A(x, y, z), B(y, z), C(y, z)\}$ (or xz/xz , depending on the effective normal) also rate stable in Case A and near-stable in Case B.
- Omitting the normal or adding a row parallel to the twist axis (e.g., $\{A(x, y), B(x, y), C(x)\}$ in a near-XY geometry, or “Rule A” with the third component aligned with the twist axis) drives $\sigma_{\min}(\mathbf{J} \mathbf{S})$ down and pushes K into the unstable band, often with RMS9 noticeably larger than RMS7 (indicating overfitting of the restricted subset).

In the near-planar Case A this leads to a clear separation: the canonical families predicted by Section III dominate the top of the list, while many of the remaining combinations cluster at large K . In the more volumetric Case B, additional selections may enter the “usable” range, but Rule-A and Rule-B families remain the most reliable.

Table organization and labeling

For each case we provide two tables:

- Table I. The top-ranked selections with brief descriptors (row set), $\det R$, orthonormality error (onErr), RMS7/RMS9, and K for Case A.
- Table II. The full list of all 36 selections, sorted by K for Case B.

Takeaways for three-point practice

1. Geometry matters. Stability is not a property of a fixed nine selections, but of how the chosen rows interact with the twist axis and the effective normal of the data.
2. Rules A–B are reliable defaults. They consistently land in the best tier across disparate geometries.

A numeric gate keeps decisions objective. The normalized K provides an immediate, unit-invariant criterion to accept or reject a seven-row selection before committing to it in a pipeline.

V. RESULTS

This section reports quantitative behavior for the 36 seven-row selections on two synthetic three-point geometries. In both cases the target coordinates were generated by a non-trivial similarity transform and additive Gaussian noise (Case A: $\sigma = 5$ mm, Case B: $\sigma = 8$ mm). Each selection is evaluated by the unit-invariant conditioning K (condition number of the scaled Jacobian, Sec. IV.A), by RMS residuals on the seven used rows (RMS7) and on all nine rows (RMS9), and by standard rotation diagnostics ($\det R$, orthonormality error as onErr). Bands used. Stable $K \leq 10$; usable $10 < K \leq 30$; unstable $K > 30$.

Case A: near-planar geometry

Table I lists all 36 selections sorted by K . A clear separation emerges: selections consistent with Rule A (two full points + one twist-aware component) and Rule B (one full point + matched 2D pairs that include the local normal) occupy the top with $K \approx 4$ –6 and sub-millimetric RMS7/RMS9 (e.g., the first five rows show $K = 4.0$, $\text{RMS9} \approx 1.1 \times 10^{-3}$ m). Mid-tier choices jump to $K \approx 90$ –400, while the worst cases explode to $K \approx 4.1 \times 10^3$ and 4.3×10^3 , confirming the geometry-dependence predicted in Section III.

TABLE I. CASE A — 36 SEVEN-ROW SELECTIONS RANKED BY THE NORMALIZED CONDITIONING K . LOW- K ROWS COINCIDE WITH RULE A/B FAMILIES; HIGH- K ROWS OMIT THE EFFECTIVE NORMAL OR ADD A TWIST-PARALLEL COMPONENT.

Subset	s	Om	Phi	Kap	Tx	Ty	Tz	detR	onErr	RMS7	RMS9	K
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7801	300.005	700.002	1200.004	1.0e+00	2.6e-17	7.3e-13	1.13e-03	4.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6982	300.005	700.002	1200.004	1.0e+00	2.4e-17	6.2e-13	1.13e-03	4.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6981	300.005	700.002	1200.004	1.0e+00	1.1e-16	5.2e-13	1.13e-03	4.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7801	300.005	700.002	1200.004	1.0e+00	2.2e-16	5.9e-13	1.13e-03	4.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6990	300.005	700.002	1200.004	1.0e+00	2.2e-16	2.3e-13	7.59e-04	4.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6981	300.005	699.999	1200.004	1.0e+00	1.1e-16	6.3e-13	1.56e-03	4.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6981	300.005	700.002	1200.004	1.0e+00	1.1e-16	1.9e-13	1.08e-03	4.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7801	300.002	700.002	1200.004	1.0e+00	2.5e-16	3.2e-13	1.63e-03	4.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7801	300.005	700.002	1200.004	1.0e+00	2.2e-16	1.1e-13	4.79e-02	4.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7800	300.005	700.002	1200.004	1.0e+00	1.9e-17	7.4e-13	1.08e-03	5.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.6981	300.005	700.002	1200.004	1.0e+00	2.9e-17	4.3e-13	1.18e-03	5.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3834	3.6980	300.005	699.999	1200.004	1.0e+00	1.1e-16	2.8e-13	1.57e-03	5.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3834	3.7800	300.002	700.002	1200.004	1.0e+00	5.2e-18	4.0e-13	1.63e-03	5.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5489	-2.3218	3.7801	300.005	700.002	1200.004	1.0e+00	1.2e-16	2.9e-13	2.34e-02	90.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5359	-2.3834	3.7800	300.004	700.002	1200.004	1.0e+00	2.2e-16	2.3e-13	1.79e-02	93.8
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3317	3.6988	300.005	700.000	1200.004	1.0e+00	1.2e-16	2.9e-13	1.65e-02	93.9
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5515	-2.3835	3.7801	300.005	700.002	1200.004	1.0e+00	3.1e-17	7.8e-13	2.70e-02	104.6
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5515	-2.3834	3.7800	300.005	700.002	1200.004	1.0e+00	1.1e-16	8.0e-13	2.70e-02	104.6
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.1851	3.6998	299.999	700.002	1200.004	1.0e+00	2.2e-16	7.0e-13	1.62e-03	104.7
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3815	3.7801	300.005	700.002	1200.004	1.0e+00	2.2e-16	2.8e-13	1.62e-03	104.7
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5346	-2.3328	3.7801	300.005	700.002	1200.055	1.0e+00	2.5e-16	8.0e-13	1.71e-02	109.8
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5852	-2.3835	3.7801	300.005	700.002	1200.055	1.0e+00	1.1e-16	1.1e-13	1.57e-02	109.7
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5489	-2.3218	3.7801	300.005	700.002	1200.036	1.0e+00	3.1e-16	1.8e-13	1.47e-02	120.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5489	-2.3218	3.7801	300.005	700.002	1200.056	1.0e+00	1.1e-16	1.6e-13	2.31e-02	120.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5273	-2.3355	3.6996	300.005	700.001	1200.045	1.0e+00	2.2e-16	1.1e-13	1.45e-02	122.1
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5887	-2.3835	3.7801	300.005	700.002	1200.004	1.0e+00	2.8e-17	4.7e-13	2.27e-03	154.8
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5886	-2.3835	3.6983	300.005	700.002	1200.004	1.0e+00	1.1e-16	3.0e-13	2.23e-03	185.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5853	-2.3855	3.7803	300.005	700.002	1200.004	1.0e+00	1.2e-17	4.5e-13	4.78e-02	186.0
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5851	-2.3834	3.7801	300.005	700.002	1200.004	1.0e+00	2.2e-16	9.6e-14	1.71e-02	185.1
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5473	-2.3455	3.7801	300.006	700.002	1200.078	1.0e+00	1.6e-16	2.0e-13	2.45e-02	212.1
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.6123	-2.3835	3.7826	300.005	700.006	1200.004	1.0e+00	3.1e-16	1.6e-13	6.24e-02	376.2
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5851	-2.3834	3.7801	300.005	700.002	1200.004	1.0e+00	2.2e-16	1.1e-13	1.80e-02	388.5
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5473	-2.3455	3.7801	300.006	700.002	1200.078	1.0e+00	1.6e-16	2.0e-13	2.87e-03	400.4
AX AY AZ BX BY BZ CX CY CZ	1.0025	1.5887	-2.2990	3.7801	300.005	700.002	1199.996	1.0e+00	1.1e-16	7.7e-14	2.93e-03	402.4
AX AY AZ BX BY BZ CX CY CZ	0.9594	1.5567	-2.3821	3.8258	300.005	700.002	1200.004	1.0e+00	2.5e-16	2.1e-13	1.56e-00	405.2
AX AY AZ BX BY BZ CX CY CZ	1.0024	1.5853	-2.3837	3.6176	300.005	700.002	1200.004	1.0e+00	1.5e-17	1.0e-13	6.73e-02	430.6

Case B: general 3D geometry

Table II is more tolerant: many selections fall in the stable/usable bands (e.g., $K = 3.9$ –30), and only a minority exceed $K \approx 35$ –150. This reflects that the effective normal is not aligned with a global axis, so more combinations incidentally capture sufficient out-of-plane sensitivity. Yet the Rule A/B families remain among the best (small RMS9, consistent rotations).

TABLE II. CASE B — 36 SEVEN-ROW SELECTIONS RANKED BY K . MORE COMBINATIONS ARE ACCEPTABLE THAN IN CASE A, BUT RULE A/B OPTIONS STILL DOMINATE THE TOP TIER.

Subset	s	Om	Phi	Kap	Tx	Ty	Tz	detR	onErr	RMS7	RMS9	K
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8004	1.9858	-2.6822	500.509	999.303	1502.094	1.0e+00	1.1e-16	5.0e-13	2.84e-03	3.9
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8014	1.9856	-2.6848	500.509	999.304	1502.095	1.0e+00	1.1e-16	5.8e-13	2.24e-03	4.3
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8006	1.9858	-2.6851	500.509	999.304	1502.094	1.0e+00	1.1e-16	8.2e-13	2.33e-03	4.3
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8009	1.9856	-2.6822	500.509	999.304	1502.095	1.0e+00	1.1e-16	8.1e-13	2.33e-03	4.3
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8004	1.9858	-2.6822	500.503	999.303	1502.094	1.0e+00	1.1e-17	6.3e-13	1.89e-03	4.4
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8003	1.9858	-2.6824	500.503	999.303	1502.094	1.0e+00	2.5e-16	5.1e-13	1.99e-03	4.9
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8014	1.9856	-2.6848	500.509	999.299	1502.095	1.0e+00	1.6e-17	3.6e-13	2.56e-03	5.2
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8004	1.9858	-2.6822	500.502	999.303	1502.094	1.0e+00	1.6e-16	8.6e-13	1.55e-03	5.3
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8014	1.9856	-2.6848	500.509	999.309	1502.095	1.0e+00	1.1e-16	4.2e-13	3.53e-03	6.0
AX AY AZ BX BY BZ CX CY CZ	1.0008	-0.7994	1.9868	-2.6857	500.509	999.295	1502.094	1.0e+00	2.2e-16	2.7e-13	4.17e-03	7.9
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8004	1.9856	-2.6822	500.504	999.303	1502.095	1.0e+00	1.1e-16	5.6e-13	1.95e-03	8.5
AX AY AZ BX BY BZ CX CY CZ	1.0008	-0.8002	1.9859	-2.6821	500.502	999.303	1502.094	1.0e+00	9.2e-18	5.1e-13	2.28e-03	9.4
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8003	1.9859	-2.6826	500.510	999.304	1502.095	1.0e+00	1.1e-16	1.0e-12	4.14e-03	10.9
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7934	1.9898	-2.6831	500.510	999.302	1502.096	1.0e+00	1.1e-16	4.3e-13	5.51e-03	11.5
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7988	1.9888	-2.6824	500.511	999.303	1502.095	1.0e+00	1.1e-16	9.2e-13	5.93e-03	11.2
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7940	1.9862	-2.6831	500.509	999.302	1502.096	1.0e+00	1.1e-16	5.3e-13	5.25e-03	11.3
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8018	1.9855	-2.5975	500.508	999.315	1502.095	1.0e+00	1.1e-16	3.1e-13	6.05e-03	11.5
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7919	1.9864	-2.6846	500.509	999.299	1502.096	1.0e+00	1.6e-16	4.6e-13	6.59e-03	11.8
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7954	1.9861	-2.6846	500.509	999.302	1502.096	1.0e+00	1.6e-16	1.1e-12	4.26e-03	13.1
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8002	1.9867	-2.6822	500.503	999.303	1502.094	1.0e+00	1.1e-16	5.6e-13	1.95e-03	13.7
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8008	1.9864	-2.6821	500.503	999.304	1502.093	1.0e+00	4.7e-18	3.7e-13	2.07e-03	14.2
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8011	1.9857	-2.6188	500.510	999.304	1502.095	1.0e+00	1.1e-16	4.4e-13	7.10e-03	14.2
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7934	1.9898	-2.6831	500.510	999.302	1502.099	1.0e+00	6.4e-18	3.5e-13	7.76e-03	14.4
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7930	1.9898	-2.6832	500.508	999.303	1502.095	1.0e+00	1.1e-16	1.6e-13	4.83e-03	15.6
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7934	1.9898	-2.6831	500.510	999.302	1502.111	1.0e+00	2.5e-16	4.2e-13	8.88e-03	15.8
AX AY AZ BX BY BZ CX CY CZ	1.0006	-0.8049	1.9849	-2.6832	500.509	999.306	1502.096	1.0e+00	2.5e-16	3.9e-13	1.02e-02	18.8
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7923	1.9908	-2.6829	500.507	999.302	1502.113	1.0e+00	1.1e-16	2.9e-13	6.51e-03	19.4
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.8068	1.9820	-2.6820	500.510	999.306	1502.080	1.0e+00	1.1e-16	2.7e-13	6.17e-03	21.2
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7982	1.9903	-2.5987	500.512	999.312	1502.095	1.0e+00	1.1e-16	2.6e-13	1.04e-02	21.4
AX AY AZ BX BY BZ CX CY CZ	1.0007	-0.7871	1.9896	-2.6831	500.509	999.301	1502.096	1.0e+00	1.1e-16	9.2e-14	2.18e-02	21.8
AX AY AZ BX BY BZ CX CY CZ	1.0008	-0.8084	1.9818	-2.6810	500.512	999.305	1502.065	1.0e+00	1.1e-17	5.1e-13	1.00e-02	30.6
AX AY AZ BX BY BZ CX CY												

Minimal-data workflow.

1. Enumerate the 36 seven-row selections.
2. Initialize (e.g., Umeyama on all nine rows), then refine on each selection.
3. Record K , RMS7, RMS9, detR, orthonormality error onErr.
4. Pick the smallest- K selection (tie-break by RMS9).
5. If no selection meets $10 < K \leq 30$, acquire more information (extra coordinates/points) rather than relying on a fragile minimal fit.

VII. CONCLUSIONS

We revisited minimal seven-equation selections for the seven-parameter 3D similarity (Helmert) transformation based on three common points. The key finding is geometry-dependence: stability is not a property of a fixed set of nine combinations. Two simple geometry-aware rules

- (Rule A) two full 3D points plus one twist-aware component, and
- (Rule B) one full 3D point plus matched 2D pairs including the normal

consistently identify well-conditioned selections. A normalized, unit-invariant conditioning measure K provides an objective accept/reject criterion.

Experiments on a near-planar and a general 3D layout confirm this picture: in Case A, Rule A/B families dominate with $K \approx 4\text{--}6$, while geometry-inconsistent selections deteriorate to $K \gg 30$ (even $>10^3$); in Case B, more combinations are acceptable, yet Rule A/B remain among the best.

In this sense, our selection-and-conditioning perspective complements exact algebraic treatments of the seven-

parameter problem [3], combinatorial Gauss–Jacobi strategies [5], and the broader algebraic viewpoint advocated in geodesy [6], while also relating to Procrustean extensions beyond seven parameters [7].

This work complements [4], where multiple seven-parameter solutions are combined via a Jacobi-type weighted average. Our results supply a principled pre-selection and weighting criterion: compute K for each seven-row solution, discard high- K subsets (e.g., $K > K_{max} \approx 30$), and weight the retained ones inversely with K^2 (optionally with RMS7). In our tests this improves the stability and accuracy of the final averaged parameters without altering the core numerical machinery of [4].

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Ensuring Building Stability with Intelligent Monitoring Systems

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Abstract—Building monitoring represents a systematic process of assessing the technical condition of structures to ensure stability and safe exploitation. Conventional monitoring methods typically rely on direct visual inspections and basic measurement tools, while special monitoring is applied when predefined thresholds are exceeded, involving targeted, periodic investigations of specific parameters related to structural stability. Recent advances in sensor technologies and Internet of Things (IoT) solutions enable continuous data acquisition, visualization through dashboards, and the implementation of automated alert mechanisms. By integrating data collection at the perception layer with advanced analysis and interpretation at the intelligent layer, modern monitoring systems provide comprehensive insights into building performance. This paper presents an overview of IoT-based solutions in enhancing building stability assessment and preventive maintenance.

Keywords—building stability, intelligent monitoring system, sensors and IoT solutions, data acquisition, visualization and analysis

I. INTRODUCTION (HEADING 1)

In recent decades, the accelerating impacts of climate change have amplified natural and anthropogenic processes that affect ground stability. Phenomena such as soil subsidence, slope failure, flooding, and tectonic displacement induce structural deformations that may compromise the safety and serviceability of built environments. The affected domains extend beyond functional infrastructure to include assets of historical, cultural, and archaeological significance, where irreversible damage may result in partial or total collapse [1], [2].

Effective monitoring, therefore, becomes an indispensable component of modern construction management and urban resilience strategies. Monitoring involves systematic, repeated spatial measurements, followed by data recording, processing, and analysis to evaluate variations in structural response and ground conditions over time. The outcomes of such analyses directly support compliance with resistance, stability, and durability requirements established in structural and environmental engineering standards [1], [2].

Building deformation is rarely the result of a single causal factor. Rather, it typically arises from the interaction of multiple geotechnical, environmental, and construction-related influences, such as [3], [1], [4]: inhomogeneous geological formations and variable soil stratification, foundation design and ground elastic resistance, freeze–thaw cycles in foundation soils, seasonal variations in temperature and humidity, improper organization or management of construction sites, structural or engineering inaccuracies, fluctuations in groundwater levels, subsurface excavation or tunneling activities, and load effects from adjacent massive structures.

The complexity of these interdependencies underscores the need for integrated monitoring systems capable of correlating multi-source data to detect anomalies and forecast structural behavior. To ensure long-term building stability and functionality, interventions are categorized into three main types [5]:

- Maintenance works: routine interventions aimed at preserving technical condition through the repair or replacement of visible components, installations, and equipment.
- Restoration works: comprehensive interventions addressing significant deterioration, including structural repair, consolidation, or reinforcement. Such works are project-based and require ongoing verification to ensure quality and compatibility with the building's existing structural system.
- Modernization works: implemented when functional or performance requirements evolve during the building's lifespan. These include reconstruction, strengthening, or reconfiguration to improve safety and operational efficiency.

II. THE ROLE OF MONITORING IN CLIMATE ADAPTATION

The concept of continuous environmental and structural observation aligns with the objectives outlined by the World Summit on Sustainable Development (2002), which defined nine societal benefit areas of Earth observation: disaster

management, public health, energy resources, climate, water, weather, ecosystems, agriculture, and biodiversity. Within this global framework, structural monitoring contributes primarily to the domains of disaster risk reduction, climate adaptation, and ecosystem protection [6].

Precise spatial and temporal monitoring enables the quantification of deformation rates, identification of instability zones, and development of predictive models that inform adaptation and mitigation strategies. Integration of intelligent monitoring systems - featuring sensor networks, satellite interferometry (InSAR), and data analytics - facilitates real-time decision-making and early-warning capabilities [2].

In Romania, the regulatory framework for structural behavior monitoring is defined by Government Decision No. 766/1997, which governs the assessment of building technical condition and operational capability. The framework establishes three primary stages:

- Monitoring During Exploitation: Identification and documentation of degradation processes.
- Intervention on Buildings: Execution of actions to maintain or improve operational capability.
- Post-Usage Phase: Safe demolition procedures, recovery of reusable materials, and assurance of environmental protection.

This legislative model highlights the importance of a life-cycle approach to building management, emphasizing monitoring as a continuous process from construction to decommissioning.

III. INTELLIGENT SYSTEMS FOR BUILDING MONITORING

Current structural monitoring represents a systematic, continuous activity designed to observe and evaluate the technical condition of a building throughout its service life. The primary objective is to maintain stability and safety during exploitation, ensuring that the structure operates within prescribed technical and functional parameters [7], [2].

When monitored parameters exceed predefined thresholds, special monitoring procedures are activated. These consist of targeted, periodic investigations focusing on parameters directly related to the structure's stability and safety. Such procedures may be established during the design phase or subsequently through technical expertise, particularly when anomalies or disturbances are detected in the building's behavior [7], [2].

The architecture of an intelligent monitoring system typically comprises three interconnected layers (Fig. 1), each fulfilling a distinct operational function [7], [2], [8]:

- Perception layer: responsible for data acquisition from the physical environment. It provides dynamic, continuous information about the building and its surroundings through: structural and environmental sensors, geodetic and geotechnical instruments, remote sensing technologies, and ground-based observation stations. These devices collectively capture parameters such as displacement, vibration, temperature, humidity, and stress distribution.
- Transport layer: ensures real-time transmission of the collected data through various communication infrastructures. It integrates: local and wireless

communication networks, edge and local servers, cloud-based storage and processing systems, remote access interfaces for authorized users. This layer guarantees secure, reliable, and uninterrupted data flow between the perception and intelligent layers.

- Intelligent layer: performs data processing, analysis, and interpretation, leveraging advanced computational technologies. Key functions include: timely storage and organization of large data volumes, analytical processing and pattern recognition, generation of diagnostic results and predictive insights, visualization through dashboards and interactive interfaces. The integration of artificial intelligence (AI) and machine learning (ML) algorithms enhances the system's capacity to detect abnormal patterns, predict failures, and issue early warnings.

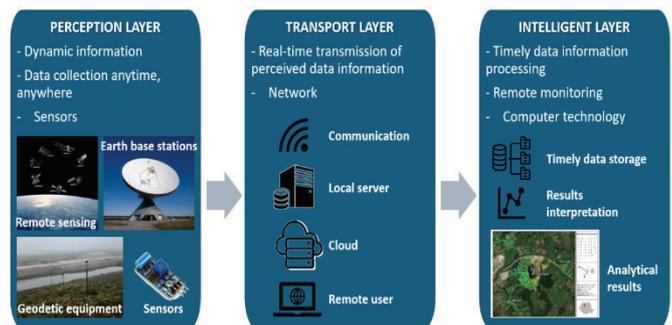


Fig. 1. Layers of the monitoring activity [2]

In the context of smart buildings, monitoring systems employ a diverse range of sensors to determine operational and environmental parameters in real time. Typical applications include [5]:

- Air quality monitoring
- Temperature and humidity control
- Ventilation management
- Fire detection and alarm systems
- Water supply and consumption monitoring
- Energy metering and optimization
- Real-time analytics for operational efficiency
- Predictive maintenance scheduling
- Connected computing for integrated system management

Modern monitoring frameworks increasingly rely on open platforms, which allow interoperability among heterogeneous devices and technologies, regardless of manufacturer. Such systems facilitate flexible configuration and gradual modernization of infrastructure by replacing obsolete or malfunctioning components with open-standard elements. This approach ensures cost-effectiveness, scalability, and technological independence, enabling users to select preferred suppliers and integrate new services seamlessly [3], [9], [4], [10].

The integration of sensors and Internet of Things (IoT) devices enables the automatic generation of interactive dashboards, graphical representations, and responsive rule sets that establish event triggers and alarm thresholds. These

tools provide real-time situational awareness for facility managers, allowing for [3], [9], [4], [10]:

- Continuous supervision of structural health and occupant comfort
- Detection of anomalies or hazardous conditions
- Optimization of energy consumption and resource management
- Rapid response to operational incidents

By combining intelligent monitoring with open digital ecosystems, buildings evolve into adaptive, self-observing entities, capable of maintaining operational stability and efficiency under dynamic environmental and usage conditions.

A. Data Collection

The data collection phase, as shown in Table 1, integrates automated procedures to acquire environmental and structural information relevant to the technical condition and performance of a building. Routine monitoring is performed at regular intervals to evaluate the overall structural state of the site and maintain operational stability throughout its service life [7], [11], [5], [2].

Geotechnical monitoring constitutes a core component of this process, involving the use of specialized instrumentation to record ground displacements, stress-strain conditions, and other variables that influence both slope stability and structural response.

TABLE I. MONITORING INSTRUMENT AND METHODS APPLIED FOR ENSURING BUILDING STABILITY

Instrument & Method / Action	Assessing Stability			Predictive Capabilities
	Detecting Terrain Settlement	Early Warning System		
High-resolution topography	X	X		
Photogrammetry / Remote sensing	X	X		
Real-time geodetic measurements	X		X	X
Temperature sensors	X	X		X
Humidity sensors	X	X		X
Vibration sensors	X	X	X	

Recent technological developments - particularly those associated with the Internet of Things (IoT) - have transformed traditional monitoring methodologies. IoT-enabled systems overcome previous limitations such as low sampling frequency and the need for extensive manual data collection by enabling real-time, high-density measurements. This allows construction and maintenance teams to

dynamically adjust operational parameters and techniques based on live data streams (Fig. 2) [2].

The integration of IoT technologies yields several significant benefits [7]:

- Continuous assessment of foundation ground stability
- Evaluation of support system integrity
- Optimization of design parameters through real-time feedback
- Improved scheduling of secondary lining installation
- Enhanced construction efficiency and safety

Through these capabilities, IoT-based monitoring supports proactive risk management and strengthens the long-term resilience of buildings and civil infrastructure [7].

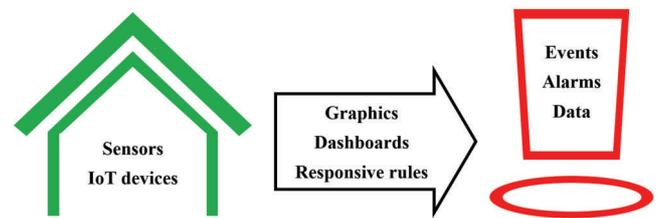


Fig. 2. Use of modern technologies in monitoring activities [2]

Beyond geotechnical measurements, monitoring of vibration effects - especially those generated by heavy traffic or industrial activity (Fig. 3) - is essential for ensuring building safety. Vibration sensors record both velocity and acceleration over time to characterize ground and structural motion. For reliable dynamic analysis, instruments should measure all three motion components (X, Y, Z) and be installed at a minimum of three representative locations [2]:

- The upper structure of the building
- The foundation level
- A nearby open-field reference site

Accurate interpretation of vibration data requires expert analysis to evaluate risk levels and to develop effective mitigation and reinforcement strategies [7], [5], [12], [2].

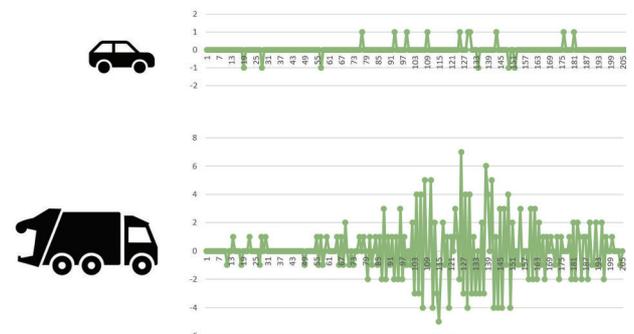


Fig. 3. Vibration caused by car vs. garbage truck

Although air temperature and humidity do not directly induce structural deformation, they exert a pronounced influence on foundation ground conditions, material integrity, and hydrological balance, all of which affect overall building stability [13], [14], [15].

Temperature is typically monitored both at the soil surface and within subsurface layers (commonly at depths of 60 cm or more) using specialized thermal probes. Empirical research demonstrates that surface temperature fluctuations can propagate to depths of up to 20 m, especially in porous or loosely compacted soils [16], [15].

Elevated temperatures cause thermal expansion of soil particles and enhance capillary rise and evaporation, altering the soil's moisture regime and potentially leading to drying and cracking of surface layers. Conversely, low temperatures induce contraction, and in regions exposed to freeze-thaw cycles, the process can generate frost heave or internal stress accumulation within the soil matrix, ultimately destabilizing the foundation or adjacent slopes [17], [16].

Alongside temperature, soil moisture is a critical determinant of ground performance. Moisture levels are monitored through air humidity sensors (for ambient conditions) and soil conductivity probes, which infer water content based on the electrical conductivity of the soil. Data interpretation must consider both moisture content and soil permeability, as their interaction governs water movement through the soil profile [14], [18], [19].

Increased soil moisture leads to higher plasticity and reduced shear strength, particularly along slopes. The angle of internal friction, which reflects the soil's resistance to particle movement, decreases with rising water content, thereby diminishing slope stability and increasing the likelihood of landslides or creep phenomena [14], [18], [19].

A comprehensive understanding of the interactions among temperature, moisture, soil mechanics, and structural behavior (Fig. 4) is crucial for maintaining both safety and environmental sustainability. The use of advanced sensors, data fusion, and predictive analytics enables early identification of risk conditions and supports informed engineering interventions [20], [21], [22].

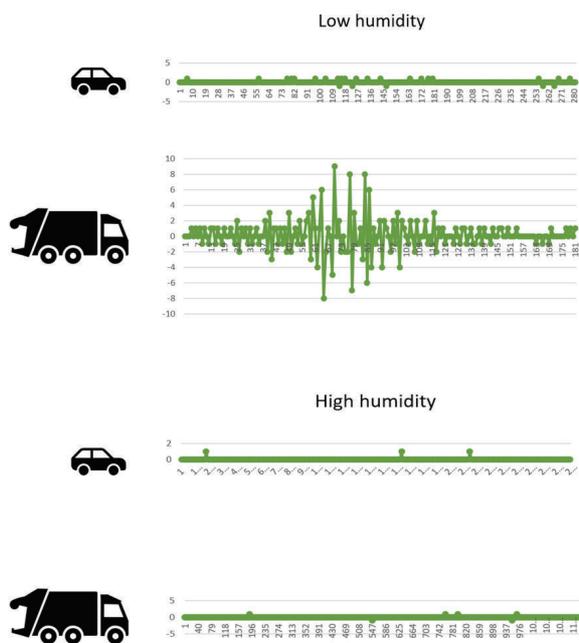


Fig. 4. Influence of humidity on vibration values

A modern monitoring network consists of a distributed array of sensors and data acquisition units, each independently

recording regional parameters such as ground movement, vibration, and environmental variables. Stations communicate with a central processing computer via digital radio links, satellite communication, cellular modems, or IoT networks, enabling remote control, real-time assessment, and system synchronization [12], [23].

Integration with Global Positioning System (GPS) modules ensures precise time alignment among regional monitoring stations, which is critical for accurate temporal correlation and comparative analysis of recorded events [12], [23].

B. Data Transmission and Management

Data obtained from diverse sensors and monitoring instruments is integrated within a centralized management platform, typically a Supervisory Control and Data Acquisition (SCADA) system or an equivalent architecture. This platform enables continuous real-time monitoring and automatically generates alerts when abnormal parameters are detected, such as atypical seepage patterns or structural deformations [2], [7].

C. Data Analysis

To achieve a comprehensive evaluation, field-acquired data are integrated through specialized analytical software that consolidates outputs from multiple monitoring instruments. This integrated approach supports advanced stability assessments by enabling the identification of spatial and temporal patterns, the detection of emerging trends, and the early recognition of potential risk conditions [2].

For higher-level analysis, a three-dimensional model of the building can be useful. Given the inherent challenges of field data acquisition and the often limited distribution of measurement points, interpolation techniques are frequently applied to estimate values in unsampled regions. Modern modeling tools provide various interpolation algorithms, and selecting the most suitable method requires a detailed understanding of each algorithm's underlying assumptions, computational behavior, and the spatial characteristics of the available dataset [2].

The accuracy and reliability of the resulting three-dimensional model depend on multiple parameters, including contour sampling density, vertical contour spacing, grid resolution, terrain morphology, and the application of spatial filters. Recent advances in terrestrial measurement technologies - such as LiDAR scanning and high-precision photogrammetry - have significantly improved three-dimensional model precision, thereby enhancing their applicability for deformation monitoring and predictive modeling of future building behavior [2].

D. Reporting and Decision Making

Effective reporting constitutes a critical component of the monitoring process, involving the systematic compilation and synthesis of collected data into structured analytical outputs. These reports present findings in a clear and visually accessible format, commonly incorporating graphs, charts, and geospatial maps to illustrate temporal and spatial variations. In addition to descriptive analytics, reports provide interpretative insights on observed trends and anomalies, along with recommendations for mitigation strategies or further data collection initiatives. To ensure regulatory compliance, all reports must conform to relevant

environmental and technical standards and be submitted to the appropriate authorities or oversight institutions [3], [4].

Based on the outcomes of the analytical assessment, management teams may implement corrective measures such as revising operational procedures, reinforcing structural components, or commissioning targeted investigations. Following each monitoring cycle, a system performance review should be conducted to evaluate data quality, measurement consistency, and network adequacy. These periodic evaluations may lead to strategic adjustments - such as the deployment of additional sensors, recalibration of existing equipment, or modification of data acquisition intervals - to enhance overall monitoring effectiveness [3], [4].

As monitoring technologies continue to evolve, the integration of advanced instrumentation, data analytics, and automation tools remains essential for improving measurement accuracy, operational efficiency, and decision-making reliability. Continuous innovation ensures that monitoring systems remain adaptable to emerging challenges and capable of supporting long-term structural stability and environmental sustainability.

CONCLUSIONS

The stability of buildings under evolving climatic and geotechnical conditions can no longer rely solely on traditional inspection methods. Intelligent monitoring systems, combining advanced sensing technologies and data analytics, provide an indispensable foundation for proactive maintenance, risk mitigation, and sustainable construction management. By integrating these systems into regulatory and operational frameworks, society can ensure the resilience of both modern and heritage structures against the accelerating challenges posed by climate change.

The assurance of building stability, durability, and sustainability depends on the continuous improvement and integration of modern, high-performance, and environmentally responsible monitoring instruments. Such systems must deliver precise, real-time data that enable proactive management of structural integrity while minimizing environmental impact and human resource demands. The adoption of these technologies enhances the ability to detect early signs of instability, optimize maintenance strategies, and ensure the long-term resilience of built environments.

Modern total stations equipped with automation and robotic control have revolutionized geodetic monitoring practices. They allow remote operation with minimal human intervention, thereby increasing safety and efficiency on construction sites. Automated tracking of targets, wireless data transmission, and real-time processing significantly improve measurement speed and precision. These instruments are essential for continuous deformation monitoring and high-frequency control of building displacement parameters.

UAV technology provides rapid, flexible, and cost-effective methods for surveying large or difficult-to-access areas. Equipped with high-resolution cameras and advanced multispectral or LiDAR sensors, UAVs capture detailed imagery and topographical data, enabling the generation of 3D terrain models, orthophotos, and volumetric analyses. These data products support the assessment of structural deformation, slope stability, and site evolution over time,

contributing to both construction supervision and environmental monitoring.

The integration of robotics and AI in the monitoring process ensures enhanced site safety, autonomous operation, and intelligent decision-making. Robotic systems perform repetitive or hazardous tasks, collect sensor data, and analyze site conditions, while AI algorithms identify anomalies and predict potential failures. These technologies provide valuable insights into operational efficiency, site health, and risk management. In building operations, AI-enabled assistants can automate environmental controls, improve energy efficiency, and deliver personalized management services.

AR and VR technologies offer transformative capabilities in surveying, design visualization, and site management. AR applications enable the real-time overlay of spatial data onto physical environments, supporting on-site decision-making and facilitating the identification of structural deviations. VR environments provide immersive 3D representations of construction sites, enhancing the understanding of spatial relationships and enabling the evaluation of complex scenarios that are difficult to interpret through conventional 2D drawings or maps.

IoT-based ecosystems interconnect surveying and monitoring instruments into a cohesive digital framework that enables real-time data acquisition, transmission, and analysis. IoT integration improves equipment interoperability, data accuracy, and maintenance efficiency, allowing for seamless communication between field sensors, processing servers, and decision-support interfaces. The combination of IoT with cloud computing and AI-driven analytics transforms raw measurements into actionable intelligence, enabling continuous, automated assessment of structural performance.

The evolution of surveying and monitoring practices reflects a dual necessity:

- Technological advancement: continuous automation reduces the need for human intervention, increasing precision, repeatability, and efficiency in measurement processes.
- Professional skill development: despite technological progress, the expertise of surveyors remains crucial. Understanding complex datasets, interpreting geotechnical behavior, and ensuring the reliability of automated systems require advanced technical knowledge and analytical competence.

The synergy between advanced technologies and human expertise defines the next generation of intelligent monitoring systems, ensuring that the principles of accuracy, safety, and sustainability remain central to modern building stability management.

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First Experiences with the AlphaEarth Foundations Model: A Cosine Distance-Based Evaluation

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The recently released AlphaEarth Foundations Model was generated using multi-source satellite data (optical, radar, LiDAR, etc.) and consists of a 64-dimensional normalized vector for each 10m by 10m pixel on the whole globe for each year since 2017.

This representation enables the use of cosine distance to quantify similarity between pixels in the parameter space. The model has been made available in Google Earth Engine, providing new opportunities for environmental monitoring. In this study, we revisited previous analyses of agricultural areas and bee pastures to evaluate the applicability of the new methodology. We compared its performance with earlier approaches based on machine learning classifiers and spectral indices calculations. Our results show that, in most cases, computations were significantly faster and required less code, while accuracy improved slightly compared to traditional methods. We also examined the spatial and temporal transferability of the approach, emphasizing its potential for broader applications in land monitoring.

Keywords: AlphaEarth Foundations Model, Google Earth Engine, cosine distance, bee pastures, satellite data, land cover analysis

I. INTRODUCTION AND METHODOLOGY

Until the appearance of AlphaEarth Foundations Model, there were relatively few success stories of AI in practical use for the Earth science community [1]. One of the research directions was establishing generative models, like DiffusionSat, that applied generative Diffusion model that performed well on many modalities (including images, speech, and video) and was tailored to support remote sensing data [2].

AlphaEarth Foundations primarily trains for distribution uniformity, and this will allow for more general-purpose tasks after training the learner for the special use case.

A. AlphaEarth Foundations Embedding model

The AlphaEarth Foundations (AEF) embedding model, developed by researchers at Google DeepMind and Google, was designed to address the challenge of creating accurate global maps from sparse and unevenly distributed ground truth data [3]. Traditional mapping efforts often rely on handcrafted features or domain-specific methods, which can be limited by noise, sensor dependence, or regional biases. AEF introduces a general-purpose geospatial representation that integrates multi-source and multi-model Earth observation data in a unified framework, enabling robust extrapolation of sparse labels into large-scale, high-resolution mapping products.

An embedding model in this context is a way of transforming diverse Earth observation inputs into a compact, universal representation. In AEF, each embedding is a 64-dimensional vector that summarizes signals from multiple modalities, including optical satellite imagery, radar, LiDAR, meteorological records, and other environmental data. These embeddings capture both spatial and temporal dynamics, making it possible to generate consistent and accurate maps even when annotated training data are scarce. By providing a common feature space for heterogeneous data sources, the model supports a wide range of applications, such as land use and land cover mapping, crop monitoring, biodiversity studies, and climate analysis.

The embeddings produced by AEF can be imagined as points distributed on the surface of a 64-dimensional unit sphere (radius = 1). Because the vectors are normalized in this way, their relative position in the embedding space encodes meaningful similarities and differences between objects or locations. This structure enables the use of cosine distance (or cosine similarity) as a metric for separating or clustering different objects: vectors that point in similar directions represent similar geospatial characteristics, while vectors that diverge more strongly correspond to distinct environmental conditions or land cover types.

B. Cosine Distance Computation

In the embedding model, each location or object is represented by a 64-dimensional vector positioned on the surface of a unit sphere. To determine how similar or different two such representations are, we can compare the angle between their vectors. This comparison is performed using cosine distance, which measures how close the orientation of two vectors is to one another. As these vectors are normalized, the cosine of their angle can be easily calculated by the dot product of the vectors, what is simply the sum of the product of the respective vector components.

If two vectors point in almost the same direction, their cosine distance is small, meaning they represent very similar geospatial characteristics. Conversely, if two vectors diverge strongly, the cosine distance is larger, indicating that the underlying environmental conditions or land cover types are different. This makes cosine distance particularly suitable for distinguishing subtle differences in complex, high-dimensional datasets like those produced by the AEF model.

For our task, implementing cosine distance means that once the embeddings are generated for the areas of interest, we can systematically compare them to evaluate their similarity. This allows us to group similar areas together,

detect boundaries between distinct land cover types, or identify unusual regions that stand out from their surroundings. In practice, cosine distance becomes a powerful tool for applying the embeddings to classification, clustering, or change detection problems without needing large amounts of labeled training data.

To make the cosine distance operational in our task, we defined a set of training areas that represent the target class or phenomenon of interest. For each training area, embeddings were extracted and then averaged to form a mean vector. This mean vector acts as a reference point in the 64-dimensional space, summarizing the typical characteristics of the training data.

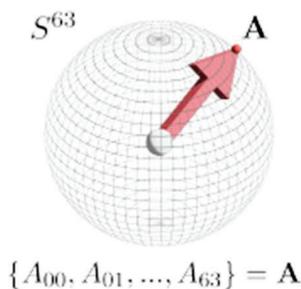


Figure 1 A stack of 64 rasterized AEF layers forms an embedding field, and each individual vector maps to a coordinate on the unit sphere S^{63} . [3]

Next, we calculated the maximum deviation from this mean vector across all training samples. This deviation serves as a threshold value in the model. In practice, when embeddings from unknown areas are compared to the mean vector, their cosine distance must remain below this threshold in order to be considered part of the same class. If the cosine distance exceeds the threshold, the area is classified as different.

- A) $A(A00m, A01m, \dots, A62m, A63m)$
 B) $B(A00, A01, \dots, A62, A63)$
 C) $\cos(\Theta) = \frac{A * B}{|A| * |B|}$
 D) $D = 1 - \cos(\Theta)$

Equation 1: Study area mean vector components (A). Components of the vector under investigation (B). Cosine similarity (C). Cosine distance (D).

This procedure ensures that the model is not overly sensitive to minor variations within the training data, while still being able to detect meaningful differences. In other words, the threshold defines how much divergence from the training examples we allow before labeling a new area as belonging to another category.

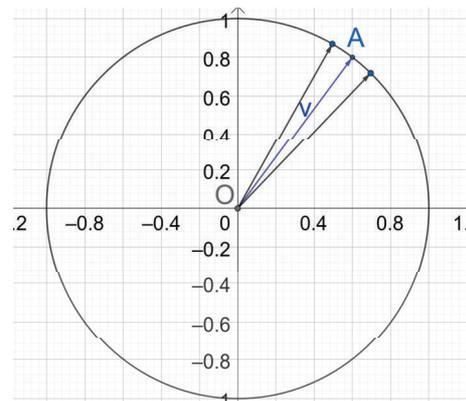


Figure 2 Mean vector of the training samples (blue) and the maximum threshold vector (black).

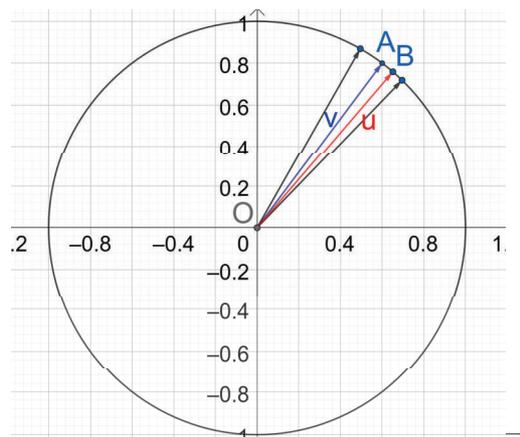


Figure 3 Example of a corresponding vector that falls within the specified threshold value (red).

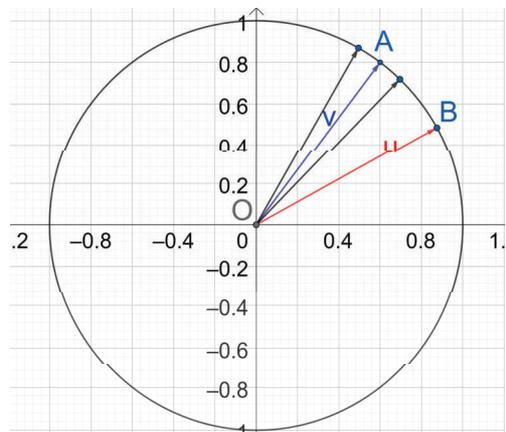


Figure 4 Example of an inappropriate vector that falls outside the specified threshold value (red).

II. RESULTS: INVESTIGATED PLANT CULTURES

The focus of our research was on the detection of various plant cultures, of which we primarily dealt with the detection of bee pastures [4].

In the framework of bee pastures, three flowering plant species of major importance for pollinators were investigated. **Rapeseed (*Brassica napus*)** is one of the most widely cultivated oilseed crops in Europe, producing large fields that bloom with abundant yellow flowers. Its high nectar and pollen production make it a crucial early spring

food source for honeybees, often contributing significantly to colony buildup after winter [5].



Figure 5 Rapeseed. source: <https://flybyjing.com/blogs/news/rapeseed-oil>

distance of pixels from the mean vector of the study area (B).
Rapeseed fields detected after masking (C).

Crimson clover (*Trifolium incarnatum*), a leguminous forage crop, is valued both for soil enrichment through nitrogen fixation and for its dense stands of red flowers that provide substantial nectar resources. It typically blooms later in the season than rapeseed, thereby extending the availability of bee pasture resources and supporting continuous foraging opportunities for pollinators. [6]



Figure 7 Crimson clover. source: <https://www.pennington.com/all-products/wildlife/resources/crimson-clover>

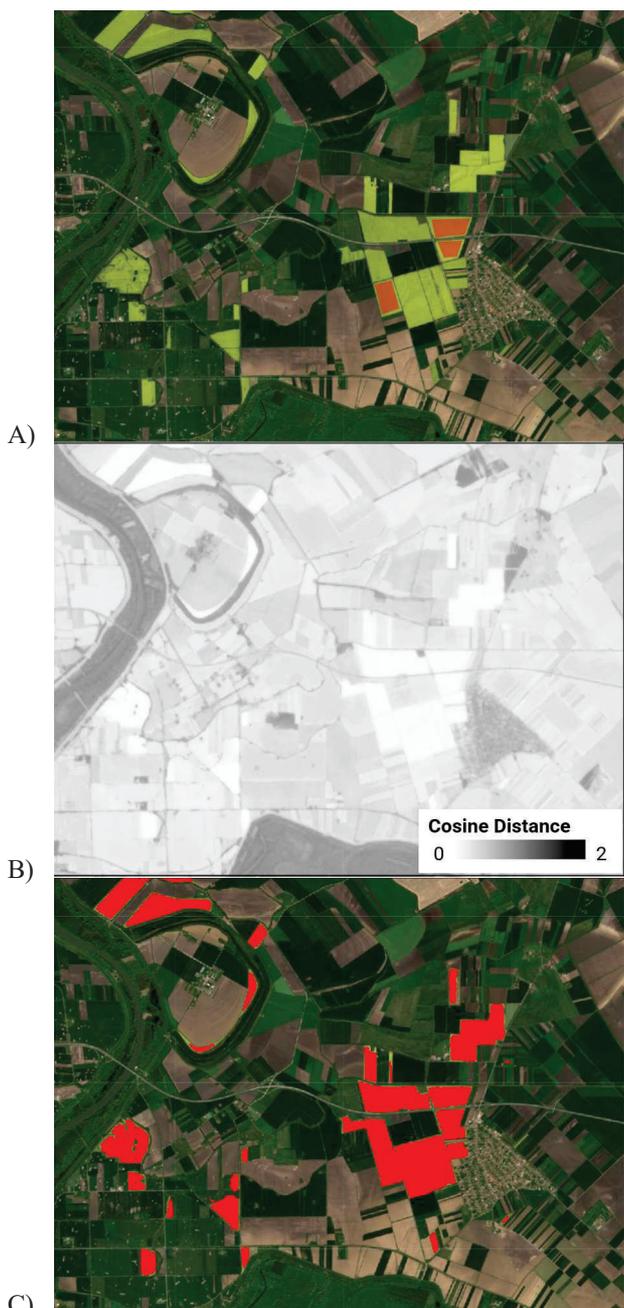
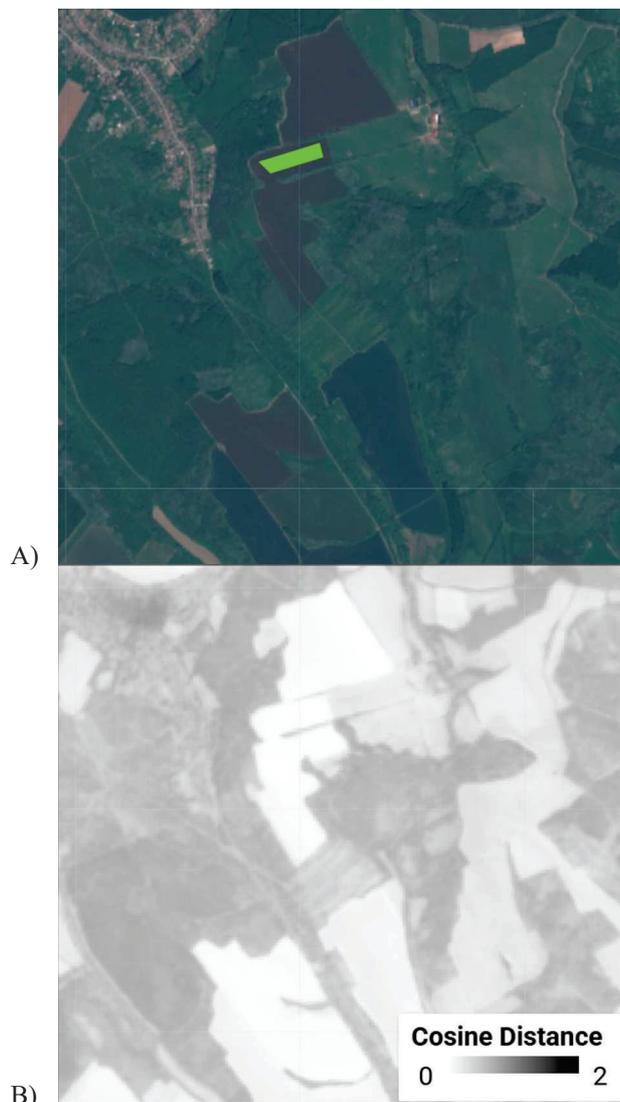


Figure 6 Detail of the rapeseed fields under investigation. The study area is shown with a red polygon (A). The cosine



B)



C)

Figure 8 Detail of the crimson clover fields under investigation. The study area is shown with a green polygon (A). The cosine distance of pixels from the mean vector of the study area (B). Crimson clover fields detected after masking (C).

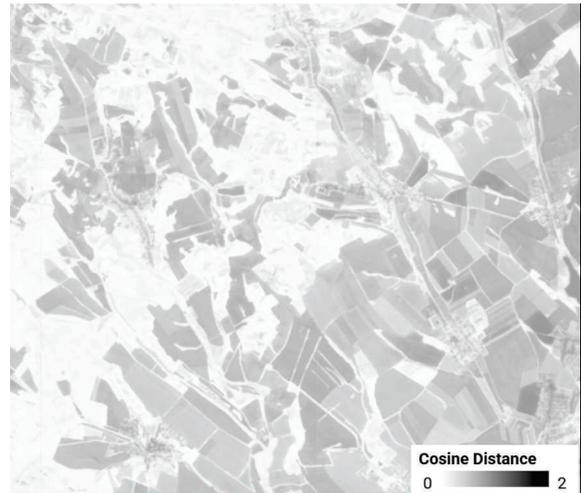
The detection of **crimson clover** (Figure 8C) also proved to be highly effective. The applied method successfully identified entire crimson clover fields, **including areas where the satellite imagery already showed signs of post-flowering vegetation**. This indicates that the embedding-based cosine distance approach can reliably detect the crop even when its phenological stage is past peak flowering, highlighting its robustness compared to methods that rely strictly on spectral signals captured at a single time point.

Black locust (*Robinia pseudoacacia*), a fast-growing deciduous tree, is highly regarded in beekeeping due to its profusion of fragrant white flowers. Its nectar is the source of one of the most prized unifloral honeys in Central Europe, commonly known as acacia honey. The species contributes greatly to bee forage, particularly in late spring to early summer, when large tracts of black locust forests bloom simultaneously.

Although **black locust** plays a central role as a bee pasture species, its **detection using only cosine distance in the embedding space was not successful**. The spectral and structural characteristics of black locust stands did not produce a sufficiently distinct signature compared to other forest types to allow reliable separation based solely on their distance from the mean training vector. As a result, the expected clear discrimination between black locust forests and other wooded areas could not be achieved through this method.

Due to these limitations, the focus was shifted from species-level detection of black locust to the **broader detection and characterization of forested areas**. Forests represent a structurally and ecologically coherent land cover type that is more readily distinguishable from other vegetation categories in the embedding space. By treating forests as a single class rather than attempting to separate individual tree species, the methodology could achieve more

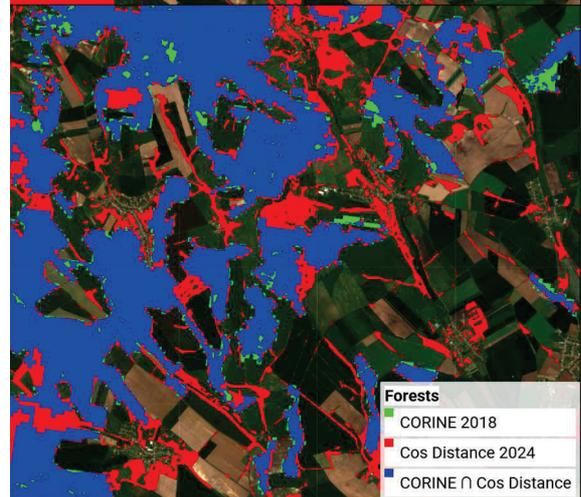
robust and consistent classification results, making it better suited for large-scale mapping tasks.



A)



B)



C)

Figure 9 Northern Hungary region, around Szirák. Cosine distance calculated from the study area (A). Detected forest areas after masking (B). Comparison of detected forest areas with the CORINE 2018 land cover database (C).

As shown in Figure 10C, there is a substantial spatial overlap between the forest areas delineated by the CORINE Land Cover database and those detected using the embedding-based methodology (blue). However, the forest areas identified exclusively by our approach (red) reveal

additional fine-scale details. This is primarily due to the higher spatial resolution of the embedding data (10 m pixel size), which enables the detection of narrow forest strips, such as tree belts along roads or small wooded patches that are not represented in the CORINE dataset.

Furthermore, part of the discrepancy arises from temporal differences between the datasets. While the CORINE Land Cover database reflects land cover conditions from 2018 (in 100 m pixel size), our analysis represents the state of 2024, capturing land cover changes that occurred in the intervening period. This includes newly established or expanded forested areas that have developed since the CORINE dataset was compiled. As a result, the observed differences reflect both improvements in spatial resolution and genuine temporal dynamics in forest cover.

III. COMPARISON WITH OTHER METHODS

When compared to other commonly used classification and change detection techniques, the cosine distance-based analysis of the embedding model demonstrates both notable strengths and clear limitations. The primary advantage of this approach lies in its conceptual simplicity and efficiency: by relying on the geometric relationships between normalized embedding vectors, it enables the identification of areas with similar environmental and spectral characteristics without the need for large annotated training datasets or complex model retraining. This makes the method particularly attractive for rapid assessments and for applications where labeled reference data are limited.

At the same time, the cosine distance approach is inherently sensitive to intra-class variability and subtle differences between land cover types, which can limit its discriminative power in more complex scenarios, such as distinguishing between tree species or different crop types with overlapping phenological patterns. Compared to supervised machine learning classifiers or advanced segmentation algorithms, cosine distance tends to perform best at broader class levels, where the within-class variability is relatively low (e.g., forest vs. non-forest), while more specialized methods may outperform it at finer thematic resolutions.

Overall, the comparison indicates that cosine distance analysis represents a robust and scalable baseline method, which can be effectively applied for large-scale mapping tasks or as a complementary step prior to more sophisticated classification approaches.

A. Comparison of Rapeseed Detection: Random Forest vs. Cosine Distance

In the detection of rapeseed, a comparison was made between a Random Forest classifier and the cosine distance-based embedding approach. Random Forest represents a machine learning-based method that requires the algorithm to learn both the characteristics of the target class (rapeseed) and the non-target classes (non-rapeseed) [7]. To achieve reliable performance, the training dataset must contain a large and diverse set of samples representing non-rapeseed surfaces, capturing the full range of spectral and temporal variability present in the study area. This typically necessitates the delineation of multiple, well-distributed

training areas. In addition, the implementation of the Random Forest algorithm involves a more complex workflow, including data preprocessing, feature selection, hyperparameter tuning, and model validation.

In contrast, the cosine distance method leverages the properties of the embedding space to separate rapeseed fields from other land cover types using only a few representative training areas. By calculating a mean embedding vector for known rapeseed fields and applying a cosine distance threshold, the method can identify rapeseed areas without explicitly providing the model with examples of non-rapeseed. This results in a simpler algorithmic setup, significantly shorter processing times, and high reliability in detecting rapeseed when clear phenological signals are present in the embedding space.

Furthermore, it is important to note that Random Forest performs best when applied during the flowering period, when rapeseed fields display distinctive spectral characteristics that enable the algorithm to differentiate them from other land cover types more easily. This requires the precise selection of imagery corresponding to the flowering stage, which can vary from year to year. By contrast, the embedding model does not depend on the exact date of data acquisition. It only requires the specification of the target year, as the temporal information is inherently encoded in the embedding representation. This makes the cosine distance approach less sensitive to timing and phenological variability, further simplifying its application in practice.

B. Comparison of Rapeseed Detection: Index-Based Method vs. Cosine Distance

In addition to machine learning and embedding-based approaches, index-based methods were also evaluated for detecting rapeseed (*Brassica napus*). This approach relies on the use of spectral indices derived from satellite imagery, specifically the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Yellow Index (NDYI). NDVI is primarily used to mask out clouds and non-vegetated surfaces, ensuring that the analysis focuses only on vegetated areas. NDYI is then applied to identify rapeseed fields during their flowering stage, leveraging the strong yellow spectral signal characteristic of blooming rapeseed.

$$\text{NDYI} = \frac{B3 - B2}{B3 + B2} \quad \text{NDVI} = \frac{B8 - B4}{B8 + B4}$$

Equation 2 Normalized Difference Yellow Index (NDYI) (left), Normalized Difference Vegetation Index (NDVI) (right) [8]

A key advantage of the index-based method is that it does not require any training data, which significantly simplifies its application. When the flowering stage is well-defined and the imagery is acquired at the appropriate time, the method can achieve high detection accuracy. Additionally, the algorithm itself is computationally straightforward, even simpler than the cosine distance-based approach.

However, the limitations of this method are closely tied to timing and flowering intensity. It can only be applied during the rapeseed flowering period, as outside this window the yellow spectral signal is absent and NDYI cannot reliably

distinguish rapeseed from other crops. In cases of weaker or heterogeneous flowering, rapeseed fields may be partially or fully masked out, leading to underestimation. Another drawback is the need for manual threshold selection for NDVI values, which introduces subjectivity and may affect consistency across different regions or years.

IV. CONCLUSIONS

Overall, while index-based methods are attractive due to their simplicity and lack of training requirements, their strong dependence on precise timing and manual parameterization make them less flexible than the embedding model-based cosine distance approach for large-scale or multi-temporal analyses as summarized in Table 1.

TABLE I. Summary of the main characteristics, advantages, and limitations of the three rapeseed detection methods

Method	Training Data	Temporal Sensitivity	Complexity	Accuracy	Main Advantages	Main Limitations
Random Forest	High – target & non-target required	High – flowering period needed	High	High	Robust, detailed classification	Data- and time-intensive; precise timing needed
Cosine Distance (Embedding)	Low – few rapeseed samples	Low – only target year needed	Medium	High	Few samples, fast, temporally flexible	Less effective for subtle class differences
Index-Based (NDVI+NDYI)	None	Very high – peak flowering required	Low	High*	Very simple, fast, no training data	Manual thresholding; weak flowering may cause omission; only works during flowering

*High accuracy when applied at peak flowering with suitable threshold

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Issues related to the correction of cadastral maps in Hungary

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Abstract— The land registry map database in Hungary is continuously maintained and corrected as necessary. Deviations beyond the error limit are corrected by the Land Registry Office. This article summarizes the reasons for the deviations and the rules for correcting them. The paper also contains national statistics and examples on procedures for correcting survey, mapping, and area calculation errors.

Keywords— *land registry, cadastral map, correcting survey, thematic map*

I. INTRODUCTION

In the coming decade, the global shift toward digital land administration is set to have a significant impact on property transaction mechanisms. Hungary's scheduled implementation of the E-ING fully electronic land registry system in 2025 is an important milestone within this international context, marking the country's commitment to advanced cadastral modernization. Through initiatives such as comprehensive automation, implementation of three-dimensional property data models, and the requirement for e-procedures, Hungary aligns itself with leading European examples in digital cadastre transformation. Key Legislative and Technological Developments in Hungary [1]:

- With effect from 15 January 2025, the revised Land Register Act mandates digital processes for almost all registry procedures, except for a brief transition period where paper submissions are still possible.
- Electronic conveyancing is now obligatory: all applications for title changes, mortgages, and parcel subdivisions must be submitted online by authorized legal professionals.
- Digital records have been formally recognized as legally binding and equivalent to previous paper documents, effectively ending the maintenance of parallel physical archives.
- The central E-ING IT platform has replaced the decentralized county-level TAKARNET infrastructure, offering a unified, national solution managed by integrated modular back-office systems.
- Certain routine property transactions, such as straightforward ownership changes, are now registered automatically by the system once all typical criteria are satisfied.
- The cadastre's statutory framework also enables the future incorporation of 3D models representing property boundaries and apartment units, facilitating urban management tasks.

Other countries—including Austria, Estonia, the Czech Republic, Bulgaria, and regions within Australia—have already operated fully digital land registry systems for over a decade, demonstrating considerably faster administrative workflows. The United Kingdom, for instance, is pursuing a complete, seamless e-conveyancing system by 2027 [2].

Innovative methods employed by international peers include the Dutch Kadaster's large-scale digitization of historical maps powered by machine learning, and Singapore's land system, which connects 3D property layers with Building Information Modelling (BIM). In Sweden, blockchain-based land transfer pilots have substantially lowered settlement risks by time-stamping transactions, a model now being tested by U.S. counties and in Africa as a safeguard against title fraud. International donor initiatives, such as World Bank projects in Central Asia and Africa, promote the use of artificial intelligence in mapping unregistered land, while Portugal's BUPi platform leverages public data contributions to improve cadastral records [3].

Yet, it is important to recognize that the current national map database is a product of processes and technologies inherited from earlier surveying eras. Initially, measurements were taken with legacy tools such as measurement chains and angle prisms, and many source maps were analog, produced under diverse projection systems and instructions—ranging from stereographic and cylindrical projections to the standardized national system. When these analog materials were digitized, inconsistencies arose: while relative geometric accuracy is usually reliable, absolute position accuracy often requires post hoc adjustment, for instance with GNSS-based coordinates [4].

Correction of mapping and cadastral errors is typically initiated either ex officio or upon notification by stakeholders with surveying authority. Hungarian land registry offices are engaged in systematically addressing such inconsistencies. The overarching objective is that, after each correction, boundary points and the corresponding area calculations comply fully with the precision requirements set out in Government Decree 8/2018 (29 April 2018).

The regulations governing map corrections are rather incomplete, however there are several publications on new technologies [5] [6] [7] and their usability in mapping [8] [9] [10].

II. ANALYSIS OF CADASTRAL MAPS IN HUNGARY

This study utilized openly accessible datasets obtained through the TAKARNET platform as well as supplementary data provided by the Lechner Knowledge Centre. The

TAKARNET data comprised information on the coordinate projection systems, mapping scales, survey dates, and dates of subsequent corrections related to the digitized analog cadastral maps, covering the internal, external, and zonal territories of Hungarian municipalities. Additional insights were drawn from the Lechner Knowledge Centre regarding the number and types of cartographic instructions applied in the different municipal subdivisions, alongside records of the initiated procedures aimed at rectifying surveying, mapping, and spatial discrepancies following the digital conversion of these maps. The data screening took place on March 25, 2025. The data may be used for research purposes in accordance with the agreement between the two institutions.

Since the outer municipal areas were frequently digitized from more detailed analog sources, the analysis and resulting thematic maps focused primarily on the typically more variable inner (built-up) areas to highlight potential accuracy issues in cadastral data (Fig. 1).



Fig. 1. Difference between the land registry map and the orthophoto – Szákszend, Hungary (source: ekozmu.e-epites.hu, access date: August 25, 2025)

The spatial distribution of projection systems was examined, revealing that about 57% of the municipality internal areas are represented in the EOV (Egységes Országos Vetület - Unified National Projection) coordinate system, which includes the DAT (Digitális Alaptérkép Szabályzat - Digital Base Map Regulations) standard. Cylindrical projections such as HER (Henger Északi Rendszer -

Northern Cylinder System), HKR (Henger Középső Rendszer - Central Cylinder System), and HDR (Henger Déli Rendszer - Southern Cylinder System) account for approximately 22%, while the remaining 21% are based on stereographic projection systems. The stereographic method involves a two-step transformation: first projecting the surface of the Bessel ellipsoid onto a Gaussian sphere, followed by casting onto a tangent plane. The cylindrical projection, as defined by Antal Fasching, likewise involves a double projection, with the second step being an inclined cylindrical slit projection. The EOV system relies on the HD72 horizontal datum, founded on the International Union of Geodesy and Geophysics 1967 ellipsoid, with the map surface being an oblique intersecting cylinder. Historical note: The Rolographic Datum system dates back to 1864, the cylindrical datum to 1908, and the Uniform National Datum was introduced in 1975.

Figure 2. clearly shows that the situation is even more complicated with regard to map-making instructions than with regard to projections.

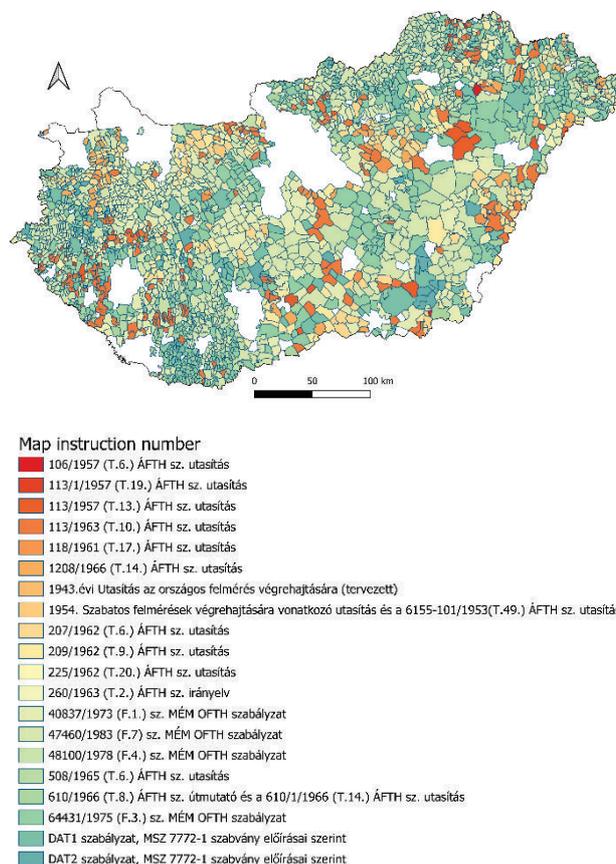


Fig. 2. Thematic map of mapping instructions (source: own editing from LECHNER source, March 25, 2025)

There are no nationwide statistics on the accuracy of maps. We can only guess at the condition of maps based on the number of map correction procedures. Since the creation of the digital map database, 63,212 procedures have been initiated in the past 18 years in the categories of surveying, mapping, and area calculation errors. Land registry officials who perform map corrections obviously have experience in this area, but this has not been published to date. The following chapter attempts to formulate principles and practical advice on this topic.

III. PROPOSALS FOR MAP CORRECTIONS

The solution is not simple and involves many factors. The recommendations for each stakeholder are listed below based on Vincze [11] [12].

- Under the guidance of the main authority
 - the differentiated quality of digital maps must be made clear at all levels;
 - the potential damage resulting from this must be anticipated;
 - lobbying (in a positive sense) must be carried out to update the data sets;
 - the representation of basic data must also be made possible in legislation, with stipulations.
- Promote the preservation of the original (good) quality of data through professional and prudent legislation.
- Uniform interpretation and application by land registries is necessary for differentiated data management.
- In the case of new surveys, consistent application of DAT regulations error limits is necessary.
- During any digital "conversion," the deviations permitted for previous mapmaking must be applied.
- Numerical data and coordinates that did not fit into inner area vector map (BEVET) must be replaced ex officio at a later date.
- After a thorough investigation of discrepancies exceeding the error limits indicated by land surveyors must be thoroughly investigated, and the necessary adjustments (corrections) must be made by the authorities.
- Newly generated original measurement results must be requested and collected and stored separately in accordance with the provisions of the new legislation (expected to be published in the near future).
- Until the new surveying program is resumed, so-called "office map updates" must be carried out, and the necessary technological requirements must be met.

Certain regulations must also be observed in relation to new surveying technologies (GPS, measuring stations):

- all points received for the work area that can be considered "identical" must be measured, at least 3-3 land parcels on each side (including the other side of the roads and the farmland side);
- check the points considered to be common using a planar similarity (Helmert) transformation – not an affine or other transformation! Points exceeding the error limit (after careful consideration, always only the most contradictory ones) must be removed from the common points;
- based on the remaining points, it must be decided: whether to keep them in place (if the point is considered identical), or e) to calculate and mark the non-identical (or non-existent) points;

- the marking must be checked by comparing it with points that can be considered identical or by repeating the marking;
- the original measurement results must be submitted for the examination and the land registry office must collect them in a separate file.

There is much to be done to improve the map database Remapping the entire system is a substantial undertaking, demanding significant financial investment and a considerable amount of time, yet it promises substantial benefits for the national economy. Increased efforts in reassessment are justified by several factors:

- establishing an accurate foundation for registration,
- providing reliable data for technical planning and operations,
- reducing the volume of complaints and legal disputes that consume administrative resources and user capacity,
- enabling businesses and organizations that rely on all supplementary location-based data to operate with much greater efficiency.

Subsequent renovation of maps created through digitization (based on field measurements) would also be useful.

Office map correction is a feasible and cost-effective technology. The basic principle of the proposed office map renewal can be summarized as follows:

- the coordinates of the digitized land parcel boundary points can be considered as preliminary data for coordinate adjustment
- based on the measurement and marking data accumulated at the land registry offices, they can be adjusted as an independent network (in a specified unit: block, section, or even parcel)
- based on the measurement and marking data accumulated by the land registries, it can be recalculated as an independent network (in a specific unit: block, section, or even location) using adjustment (i.e., the relative consistency between the field dimensions and the coordinates can be optimized);
- based on any existing or subsequently measured (e.g., with GPS) numerical points, the independent system can be "positioned" and corrected in an absolute sense; – care must be taken to transfer the inevitably changed boundary point coordinates to the connecting line sections;
- finally, the content outside the land parcel boundary breakpoints must also be transformed (if necessary) and the topological consistency must be restored.

All these tasks could be performed economically with the appropriate software support. Of course, the adjustment can be performed subject to certain constraints. The coordinates of points determined from measurements and possibly determined retrospectively (e.g., with GPS) should not change, but their preliminary (digitized) equivalents should

be included in the adjustment. Points falling within 10 cm of a straight line should belong to that line (but only if they are connected property boundary points). The measurements should be given different weights, e.g. data from before the last map update/correction should not be given half weight; – measurement/markings data created from this point onwards should be given as many weights as they occur; the dimensions of continuously measured data should be given as separate distances; control dimensions prior to setting out (which are changed by the setting out) should not be included (unless it becomes apparent from subsequent work that the field use has been left unchanged). The measurements should be used “backwards in time” (if a measurement from a later date is available and a previous one differs from it, the previous one should not be taken into account, or only after careful consideration).

To summarize the tasks, we can conclude the following:

- Land registries ought to enhance the digitized BEVET datasets by integrating numerical information, ensuring there are no inconsistencies (particularly if this step was omitted during earlier preparation).
- They should systematically request and gather original measurement records, applying differentiated approaches, while contractors are expected to cooperate, considering their long-term interests.
- Existing measurements should be leveraged to refine our databases (for instance, following the outlined methodologies).
- It is essential to actively advocate for prompt digital re-measurements, enabling us to provide the national economy with more dependable technical foundations.

IV. SUMMARY

Hungary is modernizing its land administration with the 2025 launch of the fully electronic E-ING land registry system, integrating automated decisions, 3D cadastral models, and mandatory e-procedures. This aligns Hungary with advanced European digital cadastres, improving legal frameworks and administrative workflows. The national cadastral maps, originally created using diverse analog methods and projections, suffer from heterogeneous geometric accuracy. The study uses TAKARNET and Lechner Knowledge Centre data to analyze these variations, focusing on inner municipal areas with the most significant disparities. Map correction procedures have exceeded 63,000 in 18 years, highlighting ongoing accuracy issues. Recommendations include clarifying data quality, uniform application of regulations, collecting original survey data, and advocating for digital re-measurements. Adjustments use

accumulated measurement data to enhance positional accuracy, creating a reliable technical foundation essential for efficient land administration and economic benefits.

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Comprehensive Comparative Analysis of Photogrammetric Point Cloud Generation Using Diverse Data Collection Methods

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Abstract— This study presents a detailed comparison of three data collection tools — the Ricoh Theta Z1 360° camera, Leica ScanStation C10 laser scanner, and Matterport PRO 3 mobile scanner—for generating photogrammetric point clouds. Conducted in the challenging environment of the Geoinformatics Institute’s ground-floor corridor and three additional rooms at Óbuda University, the research evaluates accuracy, compactness, ease of use, survey speed, and processing efficiency. Data processing utilized Agisoft Metashape [1], Autodesk Recap Pro [7], and CloudCompare [5], with measurements validated against a Leica Disto rangefinder. Results show the Leica C10 offers superior accuracy but is hindered by slow survey times and bulkiness, the Matterport PRO 3 balances speed and precision with VR capabilities, and the Ricoh Theta Z1 excels in rapid surveys but lacks precision. These findings guide tool selection for geospatial applications, highlighting trade-offs in accuracy, portability, and efficiency.

Keywords — Photogrammetry, Point Cloud, Ricoh Theta Z1, Leica ScanStation C10, Matterport PRO 3, Geospatial Analysis

I. INTRODUCTION

The generation of high-fidelity 3D point clouds is critical for geospatial analysis, enabling precise visualization, measurement, and modeling in applications such as building information modeling (BIM), heritage documentation, and virtual reality (VR). This study evaluates three distinct data collection tools: the Ricoh Theta Z1 360° camera [2], Leica ScanStation C10 laser scanner [3], and Matterport PRO 3 mobile scanner [4]. The test area, located at the Geoinformatics Institute, Óbuda University, includes a uniform ground-floor corridor and three additional rooms (office, classroom, and community room), selected to assess performance in both feature-scarce and complex environments. The research compares the tools based on accuracy, compactness, ease of use, survey speed, and processing efficiency, using Agisoft Metashape [1], Autodesk Recap Pro [7], and CloudCompare [5] for data processing. Measurements were validated against a Leica Disto rangefinder [6]. Motivated by a practical inquiry into 3D modeling for industrial applications, this study provides actionable insights for selecting appropriate tools for geospatial workflows.

II. SURVEY AREA DESCRIPTION

The test area comprised the ground-floor corridor of the Geoinformatics Institute, characterized by uniform checkered flooring and plain ceilings, which posed challenges for automatic point cloud alignment due to limited distinct features. Three additional rooms, an office, a classroom, and a community room—were included in the Leica C10 and Matterport PRO 3 surveys to introduce complex geometries, such as doorways and varied furniture. The Ricoh Theta Z1 survey was limited to the corridor, focusing on its panoramic imaging capabilities. The corridor’s homogeneity and the rooms’ transitional elements provided a robust testbed for evaluating tool performance.



1. Figure - Test area

III. TOOLS AND EQUIPMENT

A. Ricoh Theta Z1 360° Camera

- **Specifications:**
 - Weight: ~200 g
 - Image Resolution: 6720 x 3360 pixels
 - Video Resolution: 2K and 4K
 - Features: Compact design with dual fisheye lenses for 360° panoramic imaging, shutter speed from 1/25000 to 1/30 seconds, supported by a dedicated tripod.

- **Survey Process:** Captured 23 panoramic images along the corridor, ensuring adequate overlap without calibration markers. The camera's portability and simple interface enabled rapid data collection in minutes, ideal for quick surveys in accessible areas. [2]
- The Ricoh Theta Z1 is illustrated in the 2nd figure.



2. Figure - RICOH THETA Z1 360° camera [2]

B. *Leica ScanStation C10 Laser Scanner*

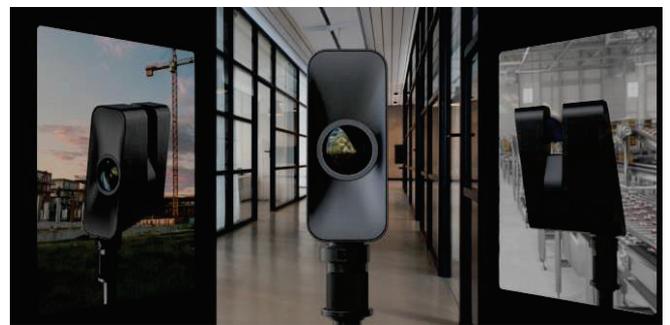
- **Specifications:**
 - Weight: ~16 kg
 - Range: 0.1–300 m
 - Measurement Speed: 50,000 points/s
 - Accuracy: Position (6 mm), Distance (4 mm), Angular (60 µrad)
 - Features: High-precision terrestrial laser scanner with integrated color camera, operating in 0°C to 40°C.
- **Survey Process:** Conducted over two days with 12 stations, using 3- and 6-inch HDS targets for alignment. Captured 260 photographs to record surface material properties (e.g., color, texture), increasing data richness but requiring significant survey time. [3]
- The Leica ScanStation C10 is shown in the 3rd figure.



3. Figure - Leica ScanStation C10 laser scanner

C. *Matterport PRO 3 Mobile Scanner*

- **Specifications:**
 - Weight: 2.2 kg
 - Depth Technology: LiDAR (Class 1, 904 nm)
 - Field of View: 360° horizontal, 295° vertical
 - Accuracy: ±20 mm at 10 m
 - Depth Resolution: 100,000 points/s, up to 1.5 million points per scan
- **Survey Process:** Utilized 38 stations, controlled via the Matterport Capture app on a Samsung tablet. Required significant overlap for automatic registration, completing the survey in minutes due to fast scan times (<20 seconds per station). [4]
- Matterport PRO 3 is depicted in the 4th figure.



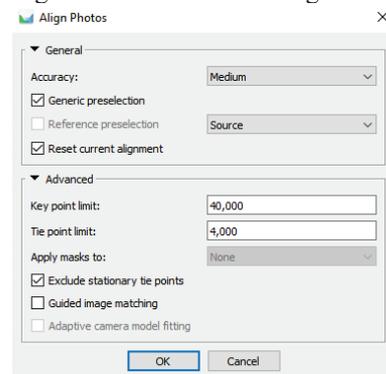
4. Figure - Matterport PRO 3 mobile scanners [4]

IV. DATA PROCESSING

A. *Ricoh Theta Z1 Processing*

The 23 panoramic images were exported as JPEG files and processed in Agisoft Metashape: [1]

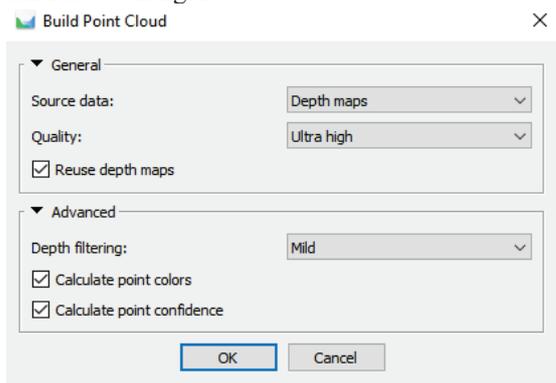
1. **Image Import and Alignment:** Imported via “Add Photos” and aligned using “Align Photos” with medium accuracy, 40,000 key points, and 4,000 tie points. No external coordinates were used, leading to potential scale inaccuracies. The alignment settings are shown in the 5th figure.



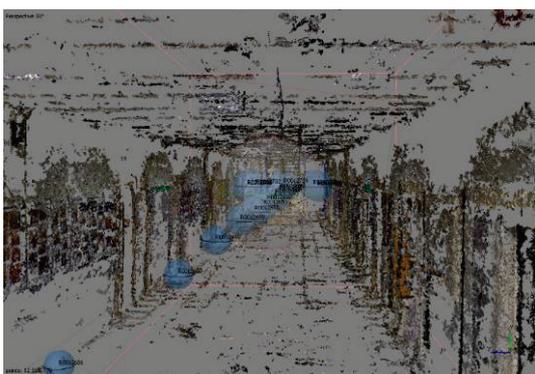
5. Figure - Align Photos settings

2. **Point Cloud Generation:** Built from depth maps with ultrahigh quality and mild depth filtering. Point colors and confidence values were calculated to enhance visualization. The resulting point cloud is

illustrated in the 7th figure, and the parameters you can see at 6th figure.

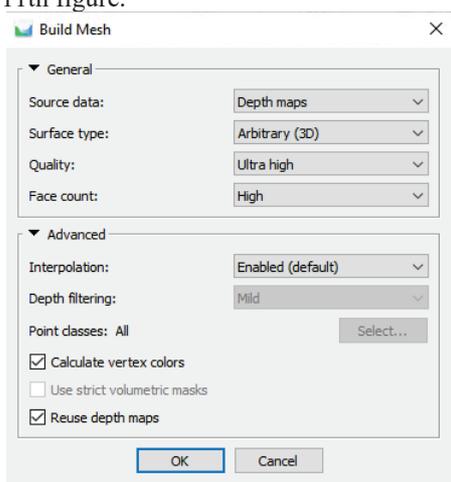


6. Figure - Point Cloud settings



7. Figure - Point Cloud of 360° camera

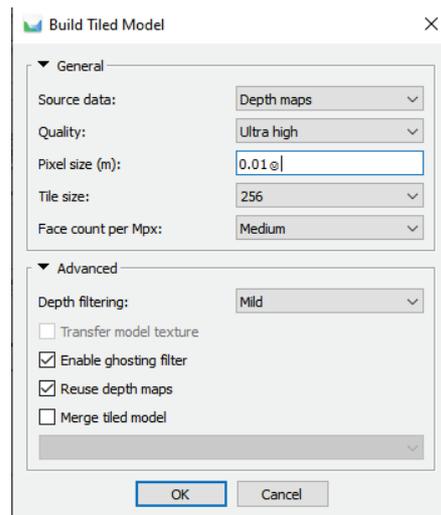
3. **Mesh and Tiled Model Creation:** Generated a mesh model, followed by a tiled model for smoother visualization, suitable for large-scale 3D modeling. The mesh model settings are shown in the 8th figure, and the resulting mesh model is depicted in the 9th figure. The tiled model settings are illustrated in the 10th figure, with the final tiled model shown in the 11th figure.



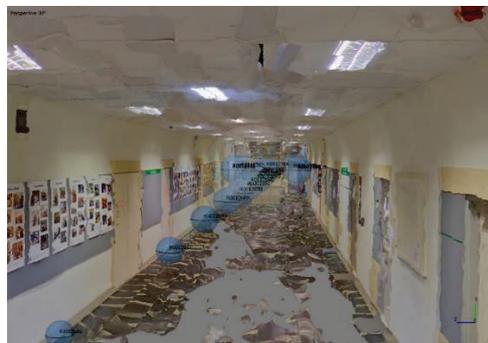
8. Figure - Mesh model settings



9. Figure - Mesh model



10. Figure - Tiled Model settings

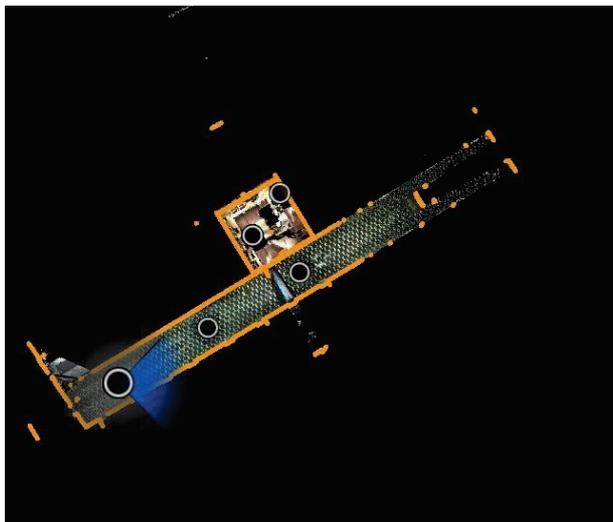


11. Figure - Tiled model

B. Leica ScanStation C10 Processing

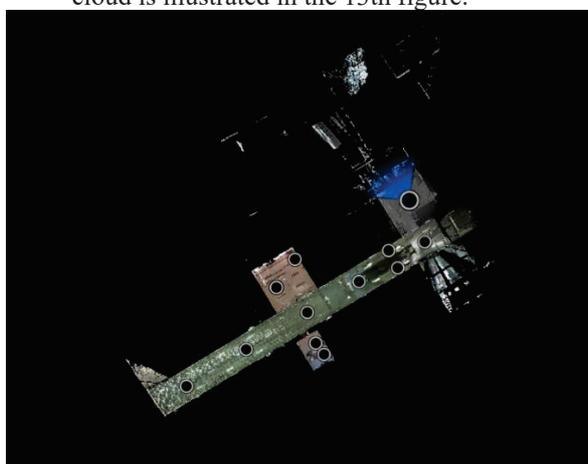
Data was processed using Autodesk Recap Pro (educational version): [7]

1. **Data Import:** Imported E57 files from 12 stations with minimal filtering to preserve data integrity.
2. **Registration:** Automatic registration failed due to corridor homogeneity, causing deformations (e.g., compressed corridor length). Manual registration used three common points per station pair, leveraging HDS targets and identifiable features (e.g., corners). The manual alignment process is shown in the 12th figure.



12. Figure - Manual alignment process on C10 scan

3. **Cleanup:** Removed noise from glass reflections, improving point cloud quality. The resulting point cloud is illustrated in the 13th figure.

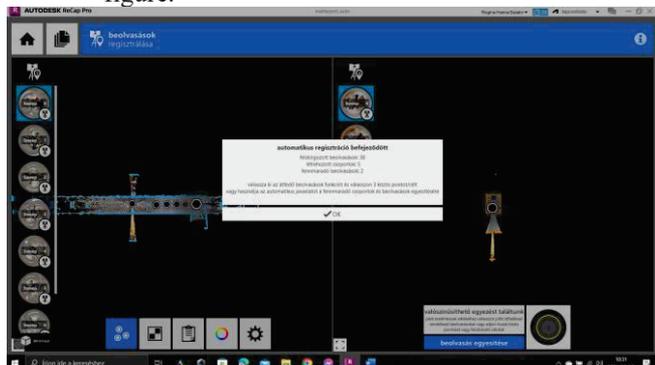


13. Figure - The result point cloud

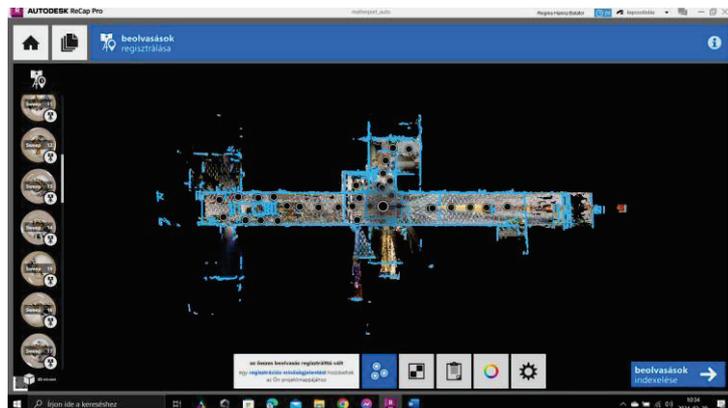
C. Matterport PRO 3 Processing

Processed in Recap Pro [7], with measurements on the Matterport VR platform:[4]

1. **Automatic Registration:** Aligned 38 stations in 10–11 minutes, with distortions in room alignments due to overlapping data. The result of automatic registration is shown in the 14th figure, with the result of automatic alignments illustrated in the 15th figure.

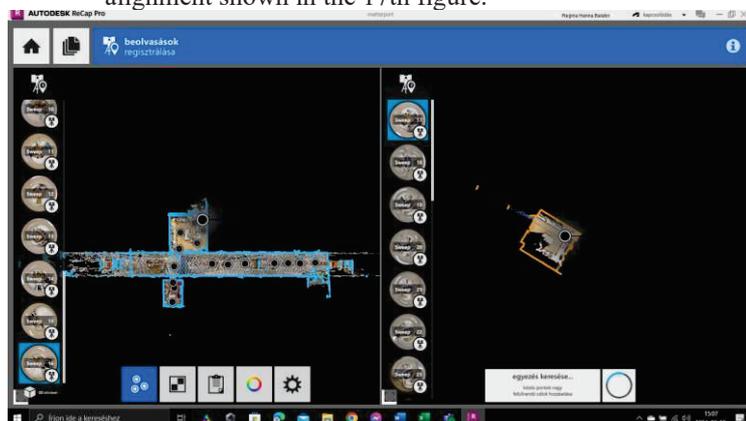


14. Figure - Result of automatic registration

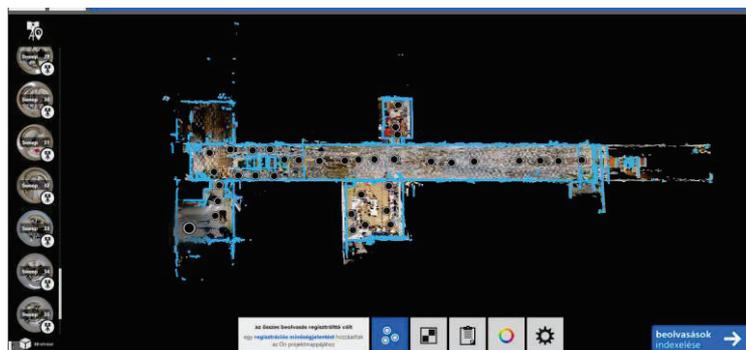


15. Figure - Result of automatic alignments

2. **Manual Registration:** Improved accuracy by manually aligning stations, addressing challenges in homogeneous areas and room transitions. The manual matching process is depicted in the 16th figure, with the position of stations after correct alignment shown in the 17th figure.

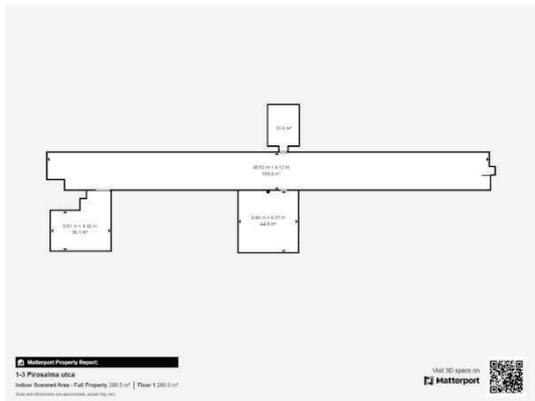


16. Figure - Manual matching process in Recap

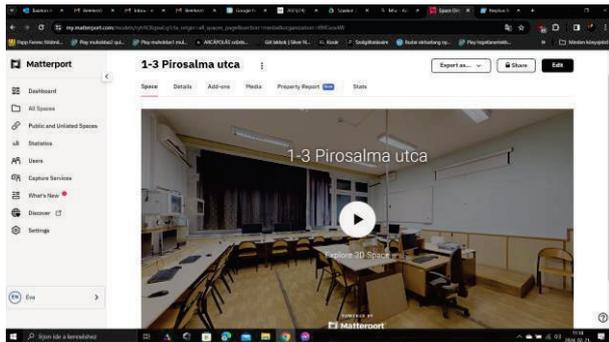


17. Figure - Position of positions after correct alignment

3. **Output:** Exported as an E57 file, with the VR platform providing walkable models and floor plans. The test area floor plan is illustrated in the 18th figure, and the Matterport website is shown in the 19th figure.



18. Figure - Test area floor plan



19. Figure - Matterport website

V. COMPARISON AND ANALYSIS

A. General Comparison

The tools were evaluated based on physical and operational characteristics:

Criteria	Ricoh Theta Z1	Leica C10	Matterport PRO 3
Weight	~200 g	~16 kg	2.2 kg
Compactness	Highly compact	Large, bulky	Compact
Ease of Use	Simple interface	Simple, technical	Simple, app-based
Survey Speed	Fast (~minutes)	Slow (~days)	Fast (~minutes)

1. table - General comparison

The Ricoh Theta Z1 and Matterport PRO 3 excelled in portability and speed, while the Leica C10 prioritized precision at the cost of time and maneuverability.

B. Measurement Accuracy

Measurements were compared with Leica Disto data: [6] The measurements on the Leica C10 point cloud in Recap are shown in the 20th figure, while the measurements on the Matterport point cloud are illustrated in the 21st figure.

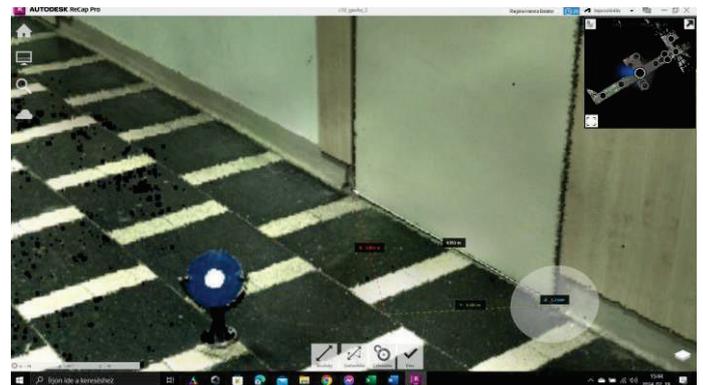
Location	Leica Disto	Ricoh Theta Z1	Deviation	Leica C10	Deviation
Corridor	4.13 m	4.18 m	-0.05 m	4.15 m	-0.02 m
Office	3.32 m	—	—	3.38 m	-0.06 m
Corridor	2.47 m	2.65 m	-0.18 m	2.47 m	0.00 m
Office	4.70 m	—	—	4.61 m	0.09 m
Classroom	1.27 m	—	—	1.23 m	0.04 m

2. table – Measuring results I.

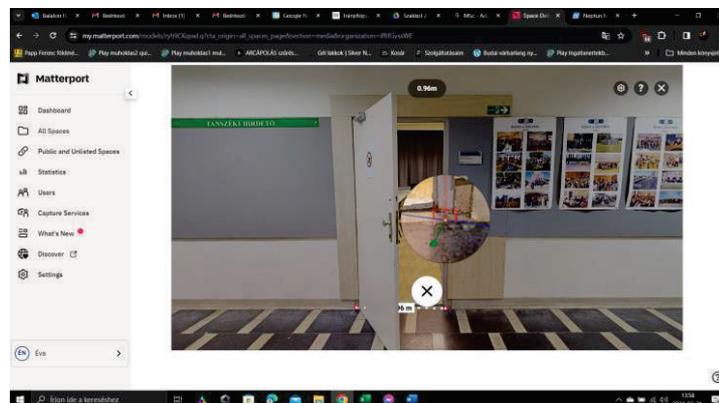
Location	Matterport (Recap)	Deviation	Matterport (VR)	Deviation
Corridor	4.13 m	0.00 m	4.12 m	0.01 m
Office	3.36 m	-0.04 m	3.36 m	-0.04 m
Corridor	2.47 m	0.00 m	2.48 m	-0.01 m
Office	4.62 m	0.08 m	—	—
Classroom	1.18 m	0.09 m	—	—

3. table – Measuring results II.

- **Ricoh Theta Z1:** Largest deviations (e.g., -0.18 m in corridor), due to sparse point clouds and lack of calibration.
- **Leica C10:** Highest accuracy (0.00–0.09 m deviations), reflecting precise laser measurements.
- **Matterport PRO 3:** Reliable accuracy (0.00–0.09 m), comparable to Leica C10, with consistent VR platform measurements.



20. Figure - Measurement in Recap on the C10 point cloud

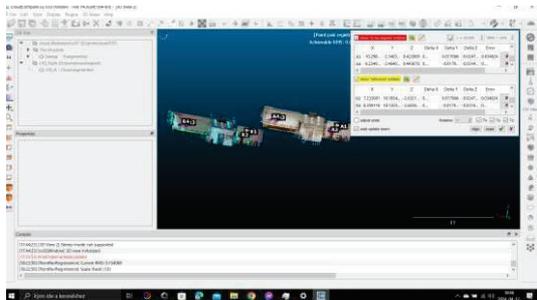


21. Figure - Measurement on Matterport

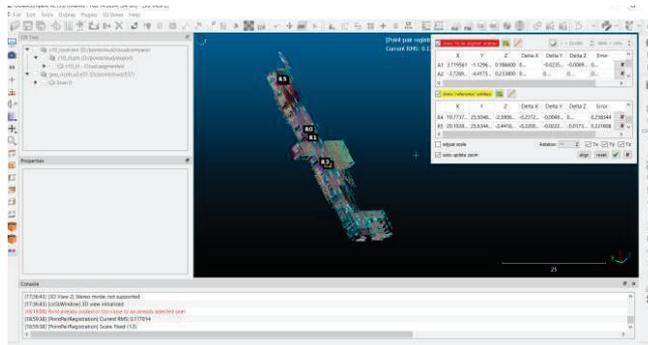
C. Point Cloud Alignment

Aligned in CloudCompare [5] using Leica C10 as the reference:

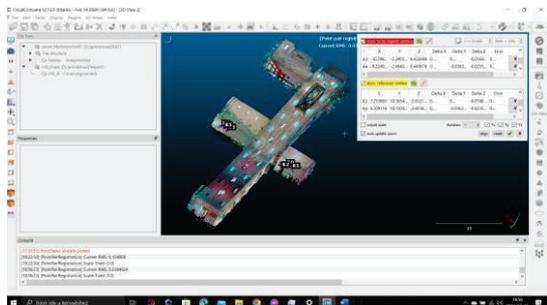
- **Matterport vs. Leica C10:** Aligned with six common points, RMS error of 4 cm, with errors near glass surfaces and staircases. The matching process of Matterport and laser scanner point clouds is shown in the 22nd figure, with the transformation result illustrated in the 23rd figure and the transformation parameters in the 24th figure.



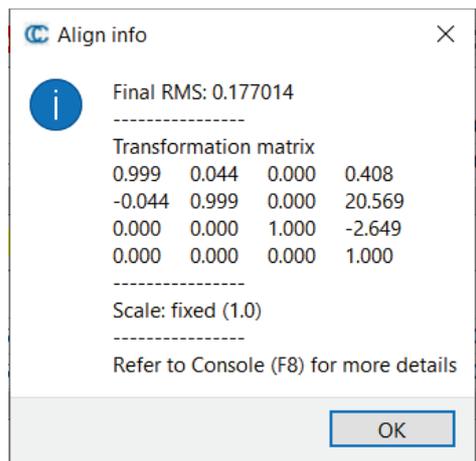
22. Figure - Matching Matterport and laser scanner point clouds



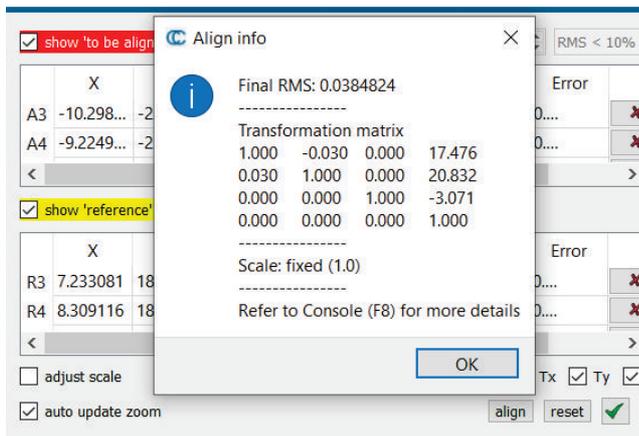
26. Figure - The result of the transformation



23. Figure - The result of the transformation

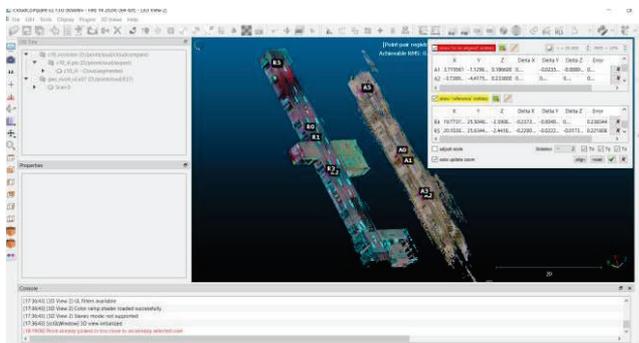


27. Figure - Transformation matrix



24. Figure - Transformation parameters

- Ricoh Theta Z1 vs. Leica C10:** Aligned with five common points, RMS error of 18 cm, due to sparse point clouds. The transformation process of the 360° camera and C10 point cloud in CloudCompare is depicted in the 25th figure, with the result shown in the 26th figure and the transformation matrix in the 27th figure.

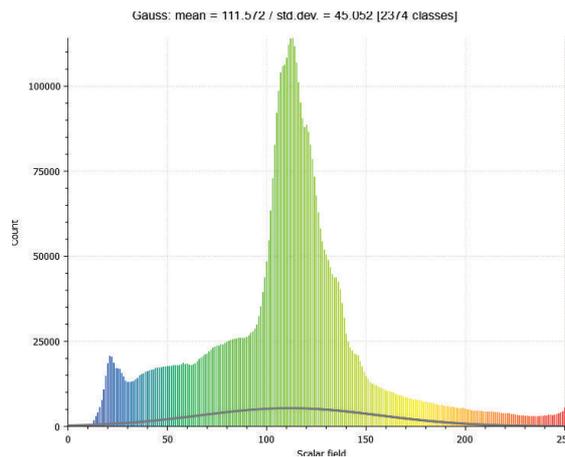


25. Figure - Transforming a 360° camera and a C10 point cloud in CloudCompare

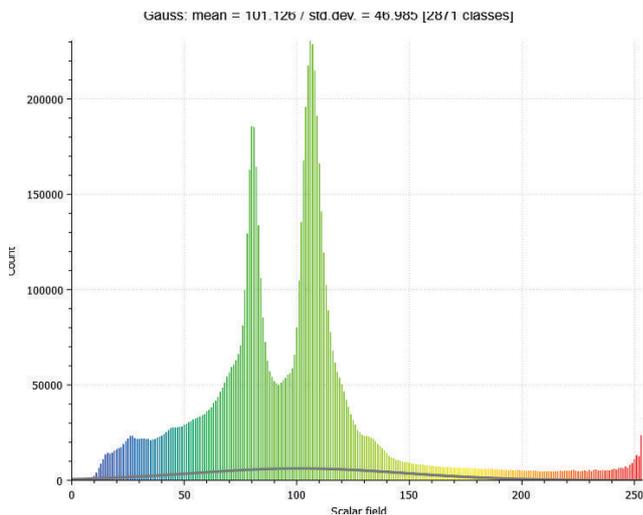
D. Error Distribution

Gaussian error distributions were analyzed:

- Office and Classroom:** Minimal discrepancies (0.04–0.08 m) for Matterport and Leica C10. The error distribution for the office is shown in the 28th figure, and for the classroom in the 29th figure.

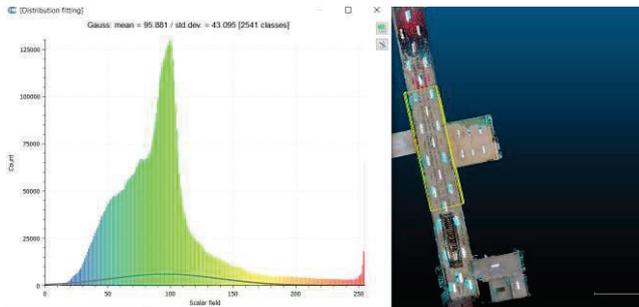


28. Figure - C10 and Matterport clouds office distribution

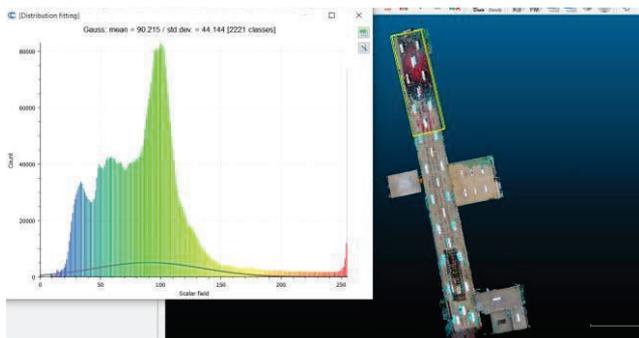


29. Figure - C10 and Matterport Cloud Classroom Distribution

- Corridor (Middle and End):** Small errors (0.00–0.01 m), effective in uniform areas. The middle piece of the corridor and its associated Gaussian error distribution are shown in the 30th figure, with the end of the corridor depicted in the 31st figure.

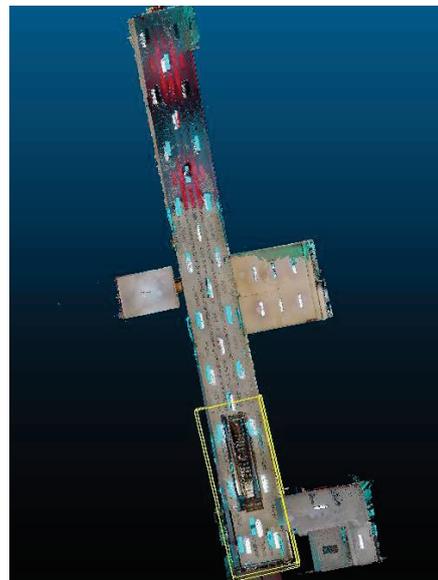


30. Figure - The middle piece of the corridor and its associated Gaussian error distribution

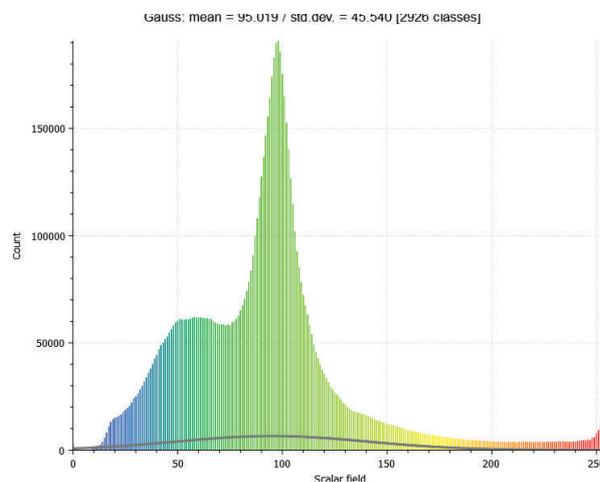


31. Figure - The end of the corridor and the associated Gaussian error distribution

- Staircase Area:** Larger errors (up to 60 cm, reduced to 15 cm with filtering) for Matterport PRO 3 due to reflective surfaces. The staircase section is depicted in the 32nd figure, with the associated error distribution shown in the 33rd figure.



32. Figure - Staircase section corridor section



33. Figure - Error distribution of the stepped part

E. Noise and Artifacts

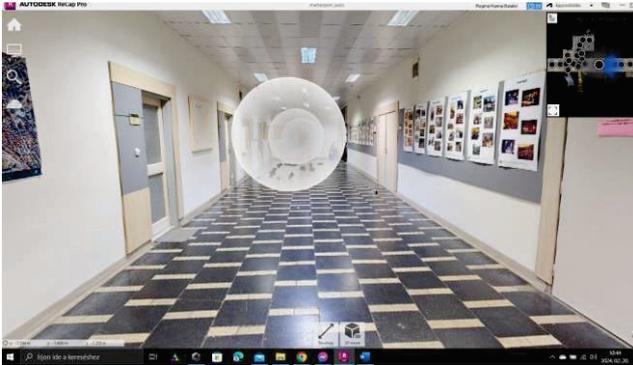
- Ricoh Theta Z1:** Noise below floor level due to fisheye lens distortions, as shown in the 34th figure.



34. Figure - Noise below floor level

- Leica C10:** Minimal noise, with artifacts from glass reflections.

- **Matterport PRO 3:** Significant noise near reflective surfaces, resulting in black spots, as illustrated in the 35th figure.



35. Figure - Black noise spots were also created when moving through the aisle positions

VI. RESULTS

- **Ricoh Theta Z1:** Completed surveys in minutes but produced sparse point clouds with deviations of 0.05–0.18 m, suitable for visualization tasks like virtual tours. [2] [6] [12]
- **Leica C10:** Achieved the highest accuracy (0.00–0.09 m deviations), ideal for precise applications, but required two days for 12 stations due to its bulkiness.
- **Matterport PRO 3:** Balanced speed and accuracy (0.00–0.09 m deviations), with VR platform enhancing visualization. Noise from reflective surfaces required manual cleanup. [12]

Challenges included:

- **Homogeneous Areas:** Uniform corridor surfaces caused alignment issues, particularly for Ricoh Theta Z1.
- **Reflective Surfaces:** Glass introduced noise, especially in Matterport PRO 3 point clouds.
- **Calibration Limitations:** Ricoh Theta Z1's lack of calibration in Agisoft Metashape reduced accuracy at image edges. [13]

VII. CONCLUSION

The choice of tool depends on project requirements:

- **Ricoh Theta Z1:** Best for rapid, low-cost surveys with moderate accuracy, [8] [10] [11] suitable for preliminary visualizations.
- **Leica C10:** Ideal for high-precision applications like structural analysis, despite slow speed and bulkiness.

- **Matterport PRO 3:** Balances speed, portability, and accuracy, suitable for BIM and VR applications.

Future research could explore hybrid approaches, combining rapid imaging with precise laser scanning, or advanced calibration techniques to enhance accuracy. Economic analyses could assess cost-effectiveness, considering equipment costs, survey time, and processing requirements.

ACKNOWLEDGMENT

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Remote Sensing and Deep Learning-Based Image Classification for Precision Agriculture

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Abstract—This Precision agriculture has become an essential approach to modern farming, aiming to optimize resource use, improve crop productivity, and ensure sustainability. A cornerstone of precision agriculture is the ability to collect, analyze, and interpret spatial and temporal information about agricultural fields. Remote sensing (RS) provides cost-effective, large-scale, and repetitive observations of crop conditions, while recent advances in artificial intelligence, especially deep learning (DL), have significantly improved the accuracy of image classification and interpretation. Integrating RS with DL techniques has therefore become a key driver of innovation in agricultural monitoring and decision support.

The aim of this study is to demonstrate how satellite data can be used to detect and map heterogeneity within fields and differences in crop growth, with particular emphasis on the application of advanced classification methods. In this study, I analyzed the spatial variability of intensively cultivated agricultural fields using several machine learning and deep learning-based algorithms (Cluster, k-means, SVM, k-NN). The results of the different classification methods were compared to identify the most effective approach for assessing crop development anomalies and supporting precision agriculture.

Keywords—Remote Sensing, Sentinel2, Deep Learning, Image Classification, Agriculture

I. INTRODUCTION

This Precision agriculture has become an essential approach to modern farming, aiming to optimize resource use, improve crop productivity, and ensure sustainability. A cornerstone of precision agriculture is the ability to collect, analyze, and interpret spatial and temporal information about and within agricultural fields. Remote sensing (RS) provides cost-effective, large-scale, and repetitive observations of crop conditions, while recent advances in artificial intelligence, especially deep learning (DL), have significantly improved the accuracy of image classification and interpretation. Integrating RS with DL techniques has therefore become a key driver of innovation in agricultural monitoring and decision support.

The application of remote sensing and deep learning in precision agriculture has gained significant attention over the past decade due to its potential to enhance crop monitoring, improve yield predictions, and optimize resource use. Remote sensing technologies, including multispectral, hyperspectral or radar (SAR) sensors, provide high-resolution, temporally-rich data that can capture crop characteristics, stress conditions, and those variability within fields [1, 2]. Remote sensing represents a robust and objective source of information for precision agriculture, providing essential data to support the assessment of within-field variability, the detection of plant stress conditions, and the planning of site-specific management interventions. The analysis of

multitemporal satellite imagery facilitates the monitoring of crop development, identification of sowing irregularities, detection of pest infestations, and evaluation of spatial variations in water and nutrient availability [3]. Nevertheless, the reliability and accuracy of such analyses are influenced by several factors, including the characteristics of the imagery and spectral indices applied, the timing of data acquisition [3], and the phenological stage of the observed crop. In addition to these factors, the choice of image classification method plays a critical role in determining the quality of the derived information. Advanced machine learning and deep learning algorithms—such as Support Vector Machines (SVM), Random Forest (RF), and Convolutional Neural Networks (CNN)—have been shown to significantly improve classification accuracy and enhance the interpretation of complex agricultural landscapes. The application of these techniques enables more reliable discrimination of crop types and stress levels, thereby strengthening the decision-support capacity of precision farming systems.

One of the studies investigated the potential of using Sentinel-2 satellite imagery combined with automatic, unsupervised classification methods to map crop heterogeneity within arable fields. The study encompassed both vegetated and non-vegetated periods and was conducted on intensively cultivated farmland. The results indicate that automatic classification can be effectively employed to identify within-field variability: spectral data clusters serve as reliable indicators of heterogeneous zones, and their statistical characteristics corroborate the presence of underlying physical differences [4, 5]. The choice of classification method significantly influences the accuracy and reliability of the derived information, thereby impacting the effectiveness of precision farming interventions.

Recent advancements in unsupervised classification techniques have further enhanced the mapping of agricultural landscapes. For instance, a multi-source unsupervised classification model (MUCCM) based on multi-scale feature aggregation networks was proposed for unsupervised crop mapping using time-series Sentinel-2 images, demonstrating improved classification performance in complex agricultural areas [6]. Additionally, a study employing time-series data and quality control procedures highlighted the effectiveness of these approaches in enhancing crop classification in complex environments ScienceDirect. These developments underscore the critical role of classification methods in precision agriculture, influencing the accuracy and reliability of information derived from remote sensing data.

Several studies have demonstrated the effectiveness of convolutional neural networks (CNNs), fully convolutional networks (FCNs), and U-Net architectures for pixel-level and semantic segmentation of agricultural fields [7, 8]. These models are particularly adept at identifying subtle differences

between crop and weed species or detecting field boundaries, outperforming traditional machine learning approaches such as support vector machines (SVM) or random forests (RF) when sufficient labeled data are available. However, model performance can vary depending on the network architecture and the specific classification task, highlighting the need for careful selection of model type based on the target crop or phenomenon.

Temporal information from multi-date satellite imagery has been shown to significantly improve classification accuracy. Recurrent-convolutional networks, which combine CNNs with recurrent layers such as LSTMs, effectively capture phenological dynamics of crops, enabling differentiation between species with similar spectral characteristics but differing growth cycles [9]. Moreover, hybrid architectures such as CNN-LSTM or CNN-GRU models demonstrate robustness to missing data due to cloud cover or sensor gaps, maintaining high classification accuracy (>85%) under realistic conditions [10].

The fusion of multispectral and SAR imagery further enhances classification performance, particularly for crops with complex structures or when optical data are limited due to atmospheric conditions [1]. Additionally, hyperspectral imaging, when combined with deep learning models, enables early detection of crop stress, nutrient deficiencies, and disease onset, exploiting subtle spectral signatures that are not easily discernible in traditional multispectral bands [2].

Despite the promising results, challenges remain in terms of data availability, annotation quality, and computational resources. Many studies highlight the need for large, accurately labeled datasets to train deep learning models effectively. Approaches such as transfer learning, data augmentation, and multi-scale feature fusion have been successfully employed to mitigate these limitations [8]. Overall, the integration of remote sensing and deep learning represents a powerful tool for precision agriculture, enabling more informed decision-making, improved crop management, and increased sustainability.

The aim of this study is to demonstrate how satellite data can be used to detect and map heterogeneity within fields and differences in crop growth, with particular emphasis on the application of advanced classification methods. In this study, I analyzed the spatial variability of intensively cultivated agricultural fields using several machine learning and deep learning-based algorithms (CLUSTER, KMEAN, SVM, k-NN, Random Forest). The results of the different classification methods were compared to identify the most effective approach for assessing crop development anomalies and supporting precision agriculture.

II. MATERIALS AND METHODS

A. Study area

Mapping of within-field heterogeneity was carried out on arable land using both supervised and automatic classification methods across several agricultural fields. However, in the present study, the analyses conducted on one representative field (Fig. 1) are presented as an example. The studied agricultural field is located in Komárom-Esztergom County, Hungary (47.595170, 18.701629). Based on precision soil sampling repeated every five years and subsequent laboratory analyses, the humus (organic matter) content varies between 1.58 % and 2.99 %. Lower organic matter content is typical of

the higher, erosion-prone parts of the field, whereas higher humus content is observed in slightly sloping or flat areas.

The soil texture index (Arany-type soil plasticity index, KA) characterizes the soil's physical texture and particle-size distribution, from which its water retention and permeability can be inferred. In the examined area, the KA values range between 37 and 45, indicating the presence of sandy loam (37), loam (38–42), and clay loam (43–45) soil types.

According to the Hungarian Soil Classification System (HSCS), the dominant soil type in the area is brown forest soil. The field is cultivated under a crop rotation system, alternating between autumn and spring arable crops. Topography has a considerable influence on land management: based on the topographic map, the highest point of the field lies at 276 m, while the lowest point is at 205 m above sea level. The area also includes slopes with gradients between 12 % and 17 %.

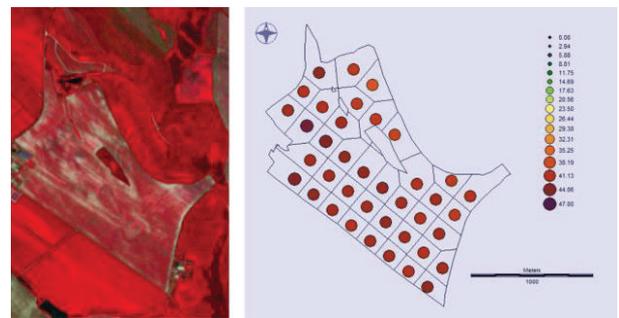


Fig. 1. Study area on satellite image (Sentinel2, 2025 June 30th) and soil sampling zones.

B. Data

Sentinel-2 comprises two satellites, Sentinel-2 A and Sentinel-2 B, which provide high spatial resolution (up to 10 m) and temporal resolution (up to 5 days) images freely. The data is available at various levels of pre-processing, including TOA and BOA. In this study Copernicus Sentinel-2 Collection 1 MSI Level-2A (L2A) Bottom of Atmosphere Reflectance Products were used. This work collected the cloud free images covering the study area in 2025 to obtain the spectral features of crops. Specifically, 6 bands including Green, Red, Near-Infrared (NIR), Short wave infrared (SWIR) 1 and SWIR2 were selected for feature extraction and classification. Behind spectral features I also selected some widely used indexes calculated from the Sentinel-2 images: the Normalized Difference Vegetation Index (NDVI) Green Vegetation Index (VIgreen) and Normalized Difference Water Index (NDWI).

The selection of satellite images was preceded by an analysis of the entire vegetation period (Fig. 2). This study focuses on the period between May and September 2025, during which 30 high-quality images (with cloud cover below 30%) were available. Time-series analysis enables the monitoring of crop development throughout the growing season. Fig. 2 shows the average NDVI values calculated for the study area. To analyze within-field heterogeneity, the period corresponding to the maximum vegetation index values (June 7–22) was selected. During this period, six high-quality Sentinel-2 images were acquired.

Ground references data included harvest (combine yield) maps, soil data, and topographic information from previous years.

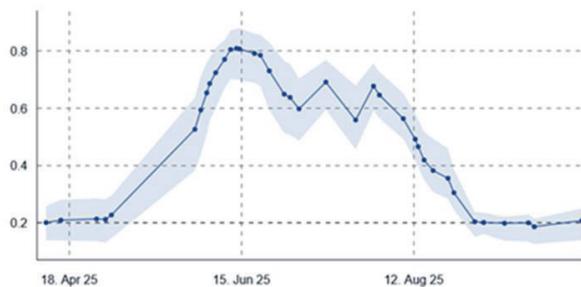


Fig. 2. Changes in the average NDVI value measured during the growing season (2025, Sentinel2)

III. MACHINE LEARNING IN IMAGE PROCESSING

Machine learning plays an increasingly important role in remote sensing and image analysis, as it enables the extraction of meaningful information from complex and high-dimensional datasets. In this context, image features—such as spectral, spatial, and textural characteristics—serve as input data for algorithms that perform image classification, pattern, and shape recognition. The machine learning process generally involves two main stages: training and evaluation. During the training phase, algorithms learn the relationships between input features and target classes based on reference (labeled) data. In the evaluation phase, the trained model is tested on unseen data to assess its accuracy and generalization ability.

Selecting an appropriate machine learning approach depends on several factors, including the research objective, the size and quality of the available dataset, and the statistical properties of the features. Machine learning algorithms are typically divided into two main categories: supervised and unsupervised learning methods. Supervised learning relies on labeled data, where the correct class of each training sample is known, while unsupervised learning identifies natural groupings or patterns in the data without prior labeling.

In this study, both supervised and unsupervised classification methods were applied to analyze spatial variability within agricultural fields. Specifically, two supervised algorithms—k-Nearest Neighbors (kNN) and Support Vector Machine (SVM)—and two unsupervised clustering approaches—the general clustering (CLUSTER) method and k-means algorithm—were used for image classification. The combination of these techniques allows for a comprehensive comparison of classification performance and supports the identification of the most effective method for detecting field heterogeneity and crop condition differences.

A. Results of Mapping Field Heterogeneity by Using Unsupervised Classification

Prior to executing the algorithm for automatic, rule-based classification, several key parameters must be defined.

- Calculation of point-to-point distances: In this study, distances are interpreted in the intensity space, and the Euclidean distance was employed to quantify them.

- Calculation of distances between clusters (classes): The simplest approach considers the average of all possible pairwise distances between points belonging to two clusters. Alternatively, distance measures derived from the probability distributions of the clusters can be used to capture more complex relationships.
- Definition of a clustering criterion: This criterion evaluates the quality of correspondence between intensity vectors and clusters. It generally favors classifications in which intra-cluster distances are minimized, while inter-cluster distances are maximized, ensuring optimal separation of spectral feature groups.

In this study, both k-means and general clustering algorithms were applied for unsupervised classification of satellite imagery. The k-means algorithm partitions data into a predefined number of clusters by iteratively assigning points to the nearest centroid and updating centroids until convergence. It is simple, computationally efficient, and widely used in remote sensing, but requires prior knowledge of the number of clusters and is sensitive to initial centroid placement. In contrast, the general clustering algorithm identifies natural groupings without predefining the number of clusters by evaluating inter-point distances and optimizing cluster assignment based on a criterion that minimizes intra-cluster variance and maximizes inter-cluster separation. While more flexible and adaptive to heterogeneous data distributions, general clustering can be computationally intensive and sensitive to parameter settings. Both methods provide complementary approaches for mapping spatial heterogeneity and extracting meaningful features from multispectral imagery.

The clustering process was carried out according to these specifications. The results of the unsupervised classification are presented in Fig. 3 where, based on the chosen parameter settings, six distinct data clusters were identified in the first step of the analysis.

Subsequently, the statistical characteristics of each cluster—such as the spectral indices and mean reflectance values of individual bands—were analyzed to support thematic interpretation. Based on this analysis, spectrally similar or small clusters were merged to form broader, thematically meaningful categories. As a result, the study area was classified into three distinct categories: average productivity, above-average productivity, and below-average productivity. In addition, the forested section within the field was delineated as a separate land-cover category.

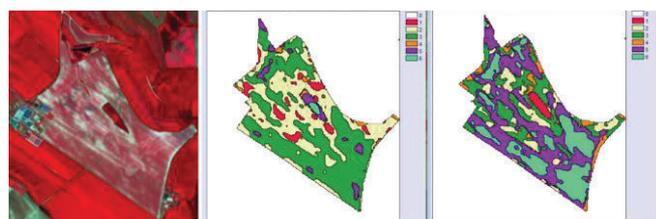


Fig. 3. Sentinel-2 image (input) and the results of two clustering procedures. The colors represent the identified clusters and do not correspond to specific thematic categories.

In the CLUSTER-based classification, two dominant clusters (72 and 99 ha) and four smaller ones (1.2–10.9 ha) were identified. The largest cluster exhibited wide internal variability (NDVI 0.25–0.51), indicating that further subdivision would have been appropriate. Moreover, parts of the forested area were misclassified together with the best-performing vegetation zones. By contrast, the k-means algorithm produced clusters whose size and spatial distribution more accurately reflected field heterogeneity. Comparison with combine harvester yield data confirmed that k-means provided a more consistent and realistic representation of the productivity patterns.

B. Results of Mapping Field Heterogeneity by Using Supervised Classification

The second part of the analysis involved supervised classification using k-Nearest Neighbors (k-NN) and Support Vector Machine (SVM) algorithms within an object-based image analysis (OBIA) framework. Prior to classification, the imagery was segmented into meaningful objects at two levels: a coarse “chessboard” segmentation defining super-level objects, and a multiresolution segmentation producing sub-level objects for finer spatial detail. From these objects, spectral, textural, and structural features were extracted, including layer values and calculated vegetation indices (e.g., NDVI, EVI, NDWI), to serve as classification attributes. Training samples (Fig. 4) were defined for three categories: average, higher than average, and lower than average crop performance.

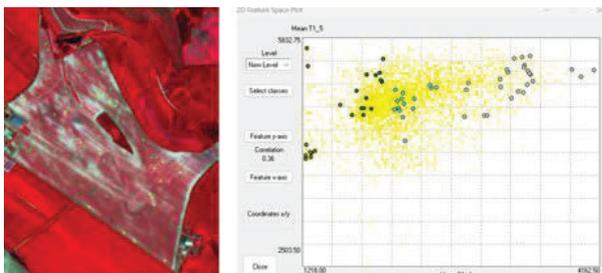


Fig. 4. The samples and their location in the feature space created by using NIR, RED bands.

Both k-NN and SVM algorithms (Fig. 5) then assigned objects to these classes based on their feature vectors. The k-NN classifier identifies the class of an object according to the majority class among its nearest neighbors, while SVM constructs an optimal hyperplane that maximizes the margin between classes in the multidimensional feature space. This supervised OBIA approach enables precise delineation of intra-field heterogeneity and provides reliable information for precision agriculture decision-making.

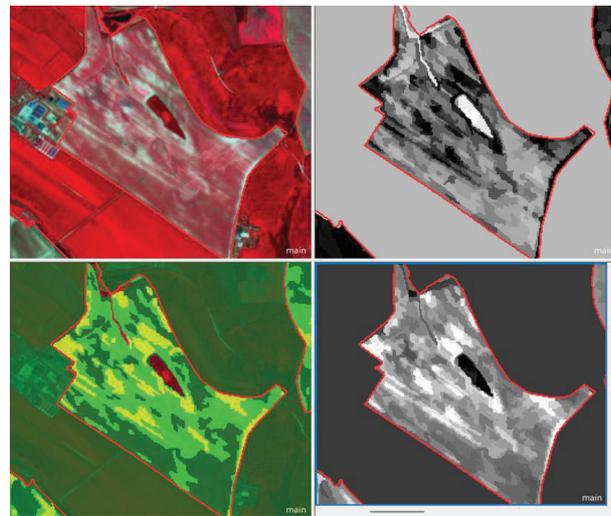


Fig. 5. Sentinel-2 image, representative grayscale feature layers used in the classification process, and the resulting land-cover map generated using the SVM algorithm.

The accuracy of supervised classification is influenced by several factors, including the outcome of the segmentation, the representativeness of the training areas, the relevance of the selected features for describing the categories, and the classification algorithm itself. In the present study, segmentation parameters were determined based on prior experience, and the results of the unsupervised classification were used to select the training areas. Features commonly applied in vegetation mapping, such as spectral indices and band values, were calculated to describe the categories. By comparing the results of multiple traditional and advanced classification approaches and harvest data (Fig. 6) it can be concluded that supervised classification provides more accurate outcomes.

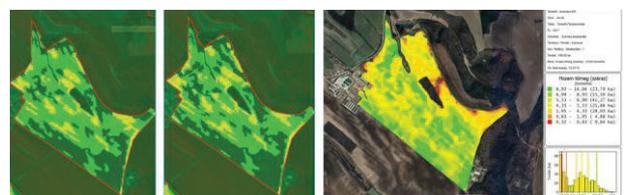


Fig. 6. Land-cover map generated using the k-NN and SVM algorithm, and harvest map

Furthermore, the spatial distribution and size of the categories showed low variability, and comparison with reference data indicated that the Support Vector Machine (SVM) algorithm yielded the most precise results.

Support Vector Machines (SVM) are supervised, non-parametric learning methods widely used in remote sensing and other fields for classification and, occasionally, regression. The principle of SVM is to represent the training objects as points in a multi-dimensional feature space and then determine the optimal hyperplane that best separates the classes. The optimal hyperplane is defined as the separating surface that maximizes the margin between objects belonging to different classes (Fig. 7).

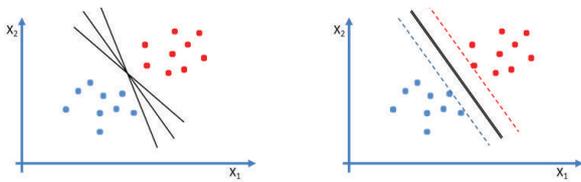


Fig. 7. Possible decision boundaries for a linear SVM (left), and the optimal decision boundary that maximizes the margin between the two categories (right)

Importantly, the classification outcome is not determined by all training points but only by those located closest to the decision boundary, known as the support vectors. This property makes SVM highly efficient, as a representative subset of the training data is sufficient to define the decision boundary accurately. equations consecutively.

IV. CONCLUSION

The overall classification workflow integrates both unsupervised and supervised approaches to maximize the detection of intra-field variability. Initially, unsupervised clustering was applied to identify natural groupings in the spectral data and explore patterns of heterogeneity without prior knowledge. These results provided preliminary insights into field variability and informed the selection of meaningful training samples for the subsequent supervised, object-based classification. By combining the exploratory power of unsupervised methods with the precision of supervised OBIA using k-NN and SVM, the workflow ensures both robust class separation and accurate mapping of crop performance across the study area. This supervised OBIA approach enables precise delineation of intra-field heterogeneity and provides reliable information for precision agriculture decision-making.

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Analysis and correction of raw WREN satellite images

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Abstract—This paper describes some research related the sensor calibration of an optical remote sensing satellite. The WREN satellite acquires multispectral images, but these raw images need some correction before any application. The columns of the image, which was created by different sensors of the camera, does not contain comparable data, the images have a striped view.

The described studies analyze the histograms of the different columns of the images and unified the the distribution for creating a corrected image or calibrate the sensor.

Index Terms—WREN, satellite image, remote sensing

I. INTRODUCTION

The WREN-1 satellite has launched in 16 August 2024 by the Falcon 9 launcher of the Transporter 11 mission[1]. This six unit size cubesat was made for the WREN (Water Resources in Efficient Networks) project to take multispectral images [2], [3], [4] for a drought monitoring system.

II. THE IMAGES

The WREN-1 satellite can take multispectral images from the Earth's surface in six bands. The image of a band contains 2048 columns and (in the examined cases) 5120 rows of 16 bit values.

The images are acquired in these bands:

- 01 Band, 445-515 nm (Blue)
- 02 Band, 505-585 nm (Green)
- 03 Band, 625-695 nm (Red)
- 04 Band, 770-790 nm (Near infrared)
- 05 Band, 890-910 nm (Near infrared)
- 06 Band, 445-805 nm (Panchromatic, not use in the described research)

When we look an image, we can see a striped pattern, because the sensors of the different columns are not uniform. (Figure 1.)

We need a method to unify the columns of the image.

There are more method for correcting the camera geometry[6], [7], but in this case we need a method for the radiometry correction of the sensors.

III. A SUGGESTED CORRECTION METHOD

The histograms can be calculated of the columns to study the differences. (Assume that columns close to each other are similar.) The following figures show the percentiles (the

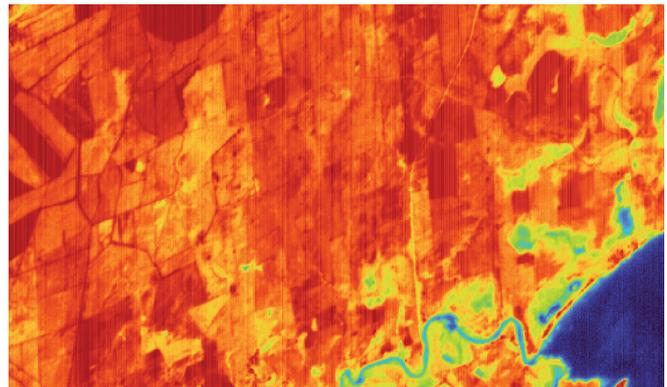


Figure 1. The view of a part of the original image in the 04 band which was taken 19 February 2025. The picture was created by QGIS [5], using a color scale, because the striping is more visible with this method.

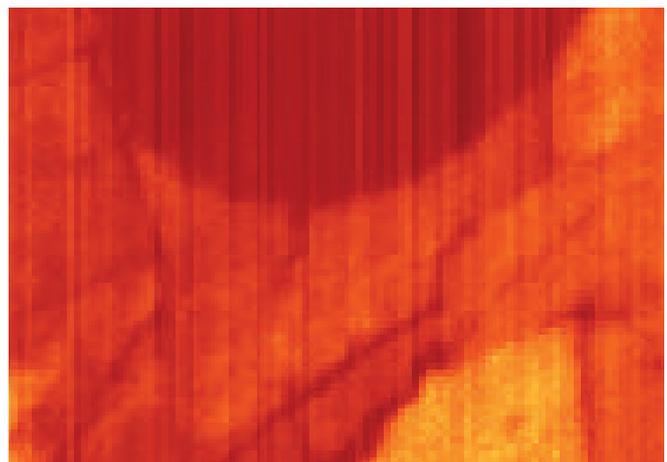


Figure 2. The enlarged view of the Figure 1.

boundaries between the percentiles) with different colors in the columns of the image.

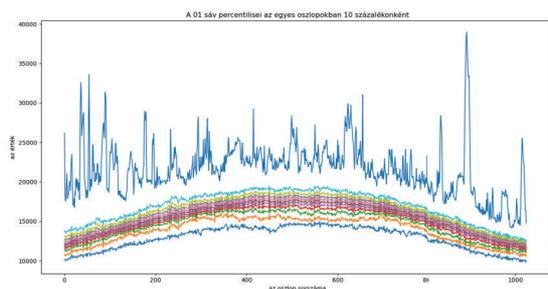


Figure 3. Distribution by percentiles in the 01 band (Blue, 445-515 nm).

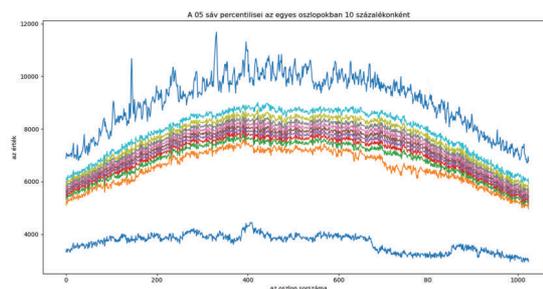


Figure 7. Distribution by percentiles in the 05 band (NIR 890-910).

We can zoom in on a part of the diagram to clearly see the differences between the columns of the image.

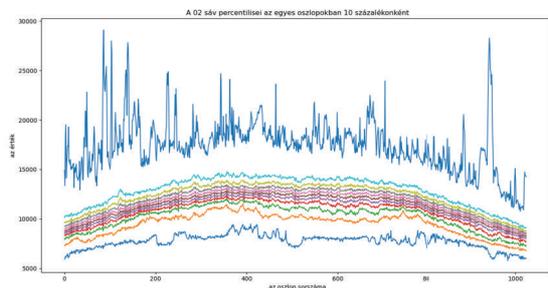


Figure 4. Distribution by percentiles in the 02 band (Green, 505-585 nm).

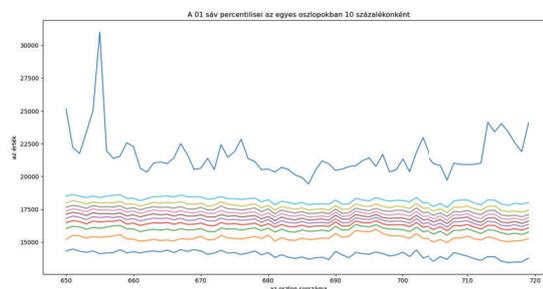


Figure 8. Distribution by percentiles in the 01 band. (zoomed part)

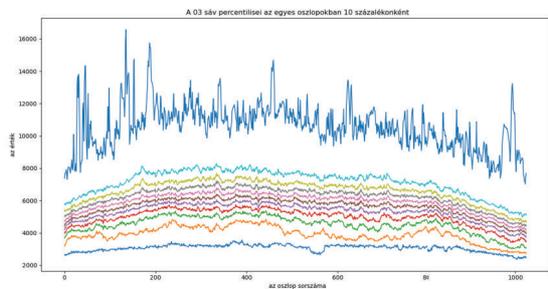


Figure 5. Distribution by percentiles in the 03 band (Red, 625-695 nm).

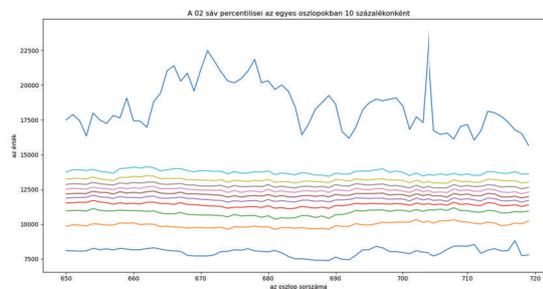


Figure 9. Distribution by percentiles in the 02 band. (zoomed part)

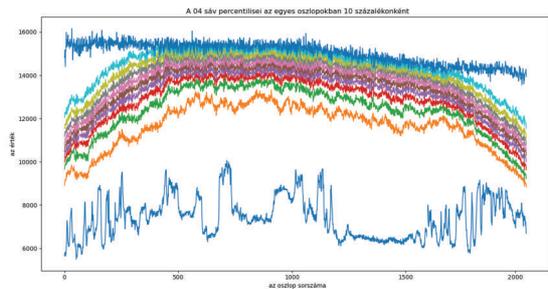


Figure 6. Distribution by percentiles in the 04 band (NIR 770-790 nm).

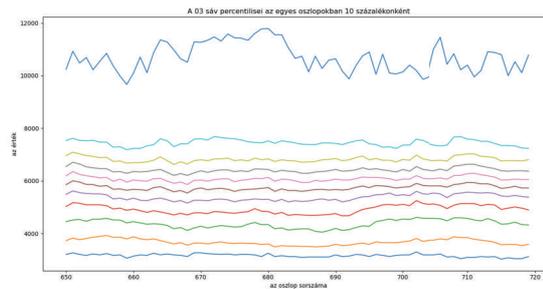


Figure 10. Distribution by percentiles in the 03 band. (zoomed part)

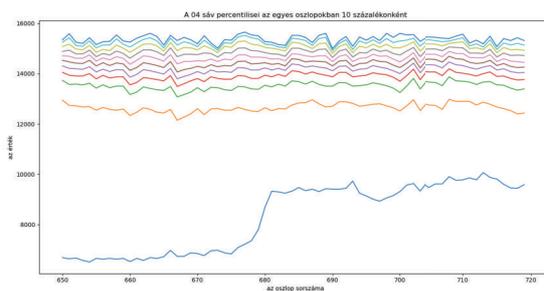


Figure 11. Distribution by percentiles in the 04 band. (zoomed part)

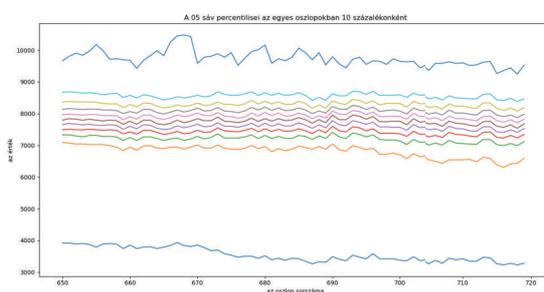


Figure 12. Distribution by percentiles in the 05 band. (zoomed part)

In the Figure 13, there are smoothing lines in dotted line. The smoothing lines created by linear regression from the neighbors (± 7) of the columns. The program fit a regression line to these 15 values, and estimate a smoothed value with the regression line in the inspected point. The program use Sector Based Linear Regression [8] which is a robust regression, the generalized process of the Fitting Disc Method [9] which developed for LiDAR data processing.

The robust regressions (like the used SBLR) can provide an appropriate result in that case too, if the dataset contains some outlier. The SBLR was used in the described analyses for this reason.

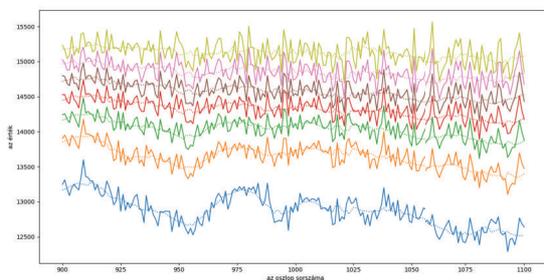


Figure 13. Distribution by percentiles in the 04 band (zoomed part) with smoothing lines (dotted lines).

The figures was created by a Python [10] program with NumPy [11] and Matplotlib [12], [13]. The source code of the program in the APPENDIX.

The program calculated a linear regression between the original and the smoothed percentiles (use also SBLR, between the 9 key values of the distributions), and apply this linear function to calculate the corrected values of the pixels of the column. This method can provide a corrected image.

IV. CONCLUSION

The result of the studied method is in the Figure 14.

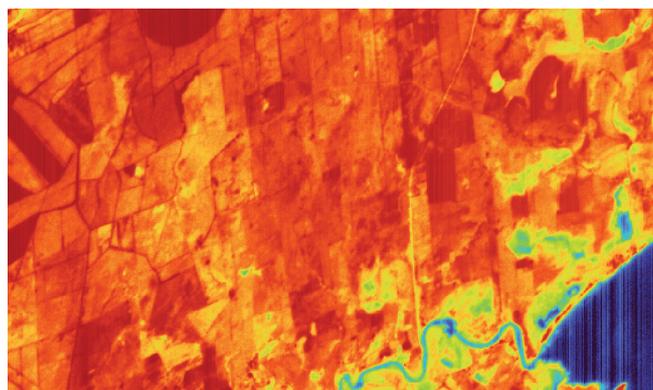


Figure 14. The corrected image (the same part and same color scale than the Figure 1.)

The striped effect are reduced in the corrected image, but has not eliminated fully, mainly the most highest values (red in the Figure 14.). In the most lowest values of the image (typically water surfaces, blue in the Figure 14.) the result are worse than in the original image.

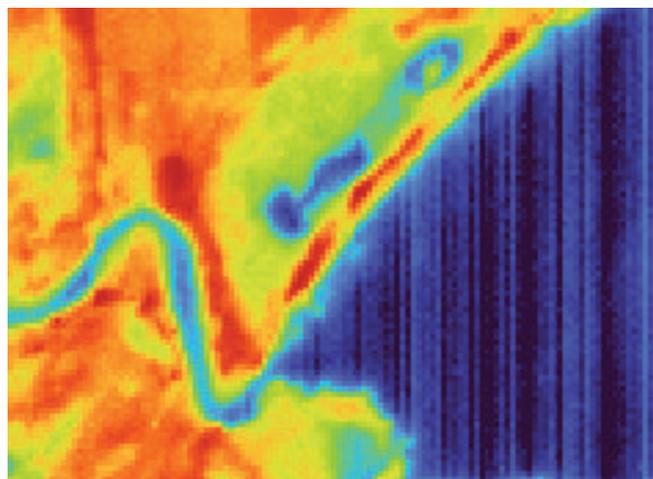


Figure 15. The enlarged view of the Figure 14.

The linear regression is not suitable for the correction in the highest and lowest parts of the histogram. In the future I can use other regression (for example polynomials) or a different linear regressions in the highest and lowest values.

An usable solution for the described problem need more research.

The usable calibration of the sensor also needs more research in the future.

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APPENDIX

```

1  #!/usr/bin/python3
2  """
3  Értékek eloszlása oszloponként és percentilisenként
4
5      \      /      I-----      I-----      I\      I
6      \      /      I-----      I-----      I \      I
7      \\/\      I \      I-----      I \      I
8
9  A programot Nagy Gábor készítette a WREN keretében
10 """
11
12 import numpy as np
13 from osgeo import gdal
14 from osgeo.gdalconst import *
15 import matplotlib.pyplot as plt
16 from sblr import sblr
17
18 def beolvas(felvetel, savok):
19     """A felvétel beolvasása sávonként egy szótárba"""
20     ret={}
21     for sav in savok:
22         kepfile=gdal.Open(felvetel+'/HICAM/band_'+sav+'.tiff', GA_ReadOnly)
23         ret[sav]=kepfile.ReadAsArray()
24     return ret
25
26 def ticklist(rnum, cmin, cmax, ticknum=7, unit=1.0):
27     """Tickerek és címkék előállítás a Matplotlib számára"""
28     rlog=np.log10((cmax-cmin)/(ticknum-1))
29     if rlog%1<=0.1505149978319906: #np.log10((1*2)**0.5)
30         rsz=1
31     elif rlog%1<=0.34948500216800943: #np.log10((2*2.5)**0.5)
32         rsz=2
33     elif rlog%1<=0.54845500650402823: #np.log10((2.5*5)**0.5)
34         rsz=2.5
35     elif rlog%1<=0.84948500216800937: #np.log10((5*10)**0.5)
36         rsz=5
37     else:

```

```

38     rsz=10
39     tickdist=int(rsz*10**int(rlog))
40     tickcoords=np.arange(tickdist*np.ceil(cmin/tickdist), cmax+0.0001, tickdist)
41     if tickdist%1==0.0:
42         ticklabels=[str(int(x*unit)) for x in tickcoords]
43     else:
44         ticklabels=[str(x*unit) for x in tickcoords]
45     ticks=[rnum*((x-cmin)/(cmax-cmin)) for x in tickcoords]
46     return (ticks, ticklabels)
47
48 szinek=['tab:gray', 'tab:blue', 'tab:orange', 'tab:green', 'tab:red', 'tab:brown', 'tab:pink',
49
50 adat=beolvas('2025_02_19T13_10_u1', ['01', '02', '03', '04', '05'])
51
52 sav='04'
53 kezd_osz=900
54 veg_osz=1100
55 ih=7
56 pctn=8
57 pctq=[i*(100/pctn) for i in range(pctn+1)]
58
59 nsor=adat[sav].shape[0]
60 nosz=adat[sav].shape[1]
61 pct=np.zeros((pctn+1,nosz))
62 pctsim=np.zeros((pctn+1,nosz))
63 for osz in range(nosz):
64     for i in range(pctn+1):
65         pct[i][osz]=np.percentile(adat[sav][:,osz], pctq[i])
66 for osz in range(ih, nosz-ih):
67     for i in range(pctn+1):
68         regegy, regegyb = sblr(list(zip(np.arange(osz-ih, osz+ih+1), pct[i,osz-ih:osz+ih+1])))
69         pctsim[i, osz] = regegy*osz+regegyb
70     if osz==ih:
71         for osze in range(ih):
72             pctsim[i, osze] = regegy*osze+regegyb
73     if osz==nosz-ih-1:
74         for oszu in range(osz+1,nosz):
75             pctsim[i, oszu] = regegy*oszu+regegyb
76

```

```
77 kezd_osz=900
78 veg_osz=1100
79
80 for i in range(1,pctn):
81     plt.plot(pct[i][kezd_osz:veg_osz+1], color=szinek[i], linestyle='-')
82     plt.plot(pctsim[i][kezd_osz:veg_osz+1], color=szinek[i], linestyle=':')
83 plt.title('A '+sav+' sáv percentilisei az egyes oszlopokban 10 százalékonként')
84 plt.xlabel('az oszlop sorszáma')
85 plt.ylabel('az érték')
86 tckx,tckl=ticklist(veg_osz-kezd_osz, kezd_osz, veg_osz)
87 plt.xticks(tckx, tckl)
88 plt.show()
89
```

SESSIONS III.

Smart Systems and Smart Manufacturing

Segmentation of Flat curves for Generating Programs for a Robotic Manipulator Performing the Functions of Processing 3D Surfaces by Applying Coatings

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Abstract — This paper presents an algorithm for approximating planar curves with conjugated circular arcs and straight-line segments. Approximation of digital planar curves using line segments and analytic curve pieces is a problem of fundamental importance in image analysis and pattern recognition. A specific variation of this problem is approximation by conjugated arcs and line segments, which also arises in robotics, particularly in motion planning. We propose an algorithmic solution to this problem, designed for the automatic generation of programs for robotic manipulators in the AS language. The originality of the method lies in employing a special representation of planar curves that is invariant under translation, rotation, and scaling. Such a representation enables the development of an optimal algorithm that automatically determines the number and placement of conjugated arcs and line segments approximating a given curve with a prescribed accuracy. The simplicity, flexibility with respect to input data, and low computational requirements of the proposed method make it suitable not only for image recognition tasks but also for robotic trajectory planning.

Keywords — approximation of planar curves, pattern recognition, motion planning, robotics.

I. INTRODUCTION

The problem of accurate geometric representation and segmentation of planar curves has long been fundamental in computer vision, image analysis, and robot trajectory planning. In modern industrial robotics, the demand for high-precision path generation has significantly increased due to the growing use of robotic manipulators in additive manufacturing, plasma spraying, and surface processing [1-3]. The ability to approximate complex trajectories by simple geometric primitives such as circular arcs and straight segments is crucial for generating executable robot programs while maintaining smooth motion and continuous curvature [4, 5].

In robotic machining and coating applications, discontinuities in curvature lead to undesirable dynamic effects, including abrupt changes in acceleration and tool

wear. Therefore, many studies focus on continuous curvature path planning (G^2 -continuity) and curvature-based representations of planar trajectories [6]. Modern approaches exploit differential geometry to describe trajectories invariant under translation, rotation, and scaling, ensuring robustness of motion planning algorithms [7].

Recent research has also emphasized shape descriptors based on curvature distributions, such as curvature-scale space and angular functions, which enable compact and invariant representations of planar curves [8, 9]. Such descriptors are widely applied not only in pattern recognition and digital shape analysis but also in the segmentation and smoothing of robot paths [10-12].

In the context of robotic program generation, segmentation of planar contours into conjugated circular arcs and straight-line segments provides a direct mapping to robot motion primitives such as MOVE and CIRCLE commands in industrial robot programming languages (e.g., Kawasaki AS, ABB RAPID, or KUKA KRL). This type of approximation ensures physically realizable trajectories and eliminates infinite acceleration points inherent in polygonal path definitions [13].

This paper presents an algorithm for approximating digital planar curves by conjugated circular arcs and line segments based on an invariant representation of the curve known as the angular characteristic function. The method automatically determines the optimal number and placement of segments to achieve a specified approximation accuracy. The proposed approach combines simplicity of implementation, low computational cost, and robustness to geometric transformations, making it suitable for both robotic trajectory planning and digital image analysis.

II. THE PROBLEM OF APPROXIMATING A PLANAR CURVE BY A SEQUENCE OF MUTUALLY CONJUGATED CIRCULAR ARCS AND STRAIGHT-LINE SEGMENTS

Some problems in motion planning and robotics require that the plane curve representing a spatial trajectory be

approximated by a special type of line, which we will call polysegment lines, defined as follows:

Definition 1. We define a polysegment line as a pair (A, B) , where $A = \{v_1, v_2, \dots, v_n\}$ is a sequence of n vertices $\forall j \in \{1, \dots, n\} v_j \in \mathbb{R}^2$ defining the polyline p , and $B = \{s_1, s_2, \dots, s_{n-1}\}$ is a sequence of $n - 1$ segments. Each segment s_k where $k \in \{1, \dots, n - 1\}$ is a plane curve with two ends at vertices v_k and v_{k-1} which is either a line segment or an arc of a circle, connecting vertices v_k and v_{k-1} . A polysegment line in which any two adjacent segments s_j and s_{j+1} are either conjugate circular arcs or a straight line segment, conjugate with an arc of a circle, we will call a conjugate polysegment line. An example of a polysegment curve is shown in Fig. 1.

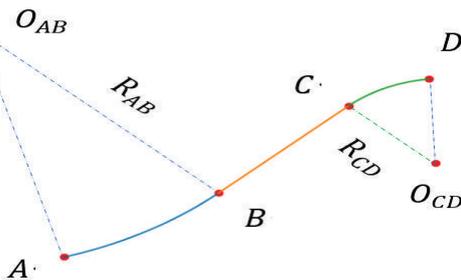


Fig. 1. Polysegment curve AD, composed of three segments AB, BC and CD, where AB and CD are circular arcs tangentially joined to the straight segment BC

As an illustrative problem arising in robotic automation of manufacturing, we address the automatic generation of an AS-language program for a robot manipulator that cuts contours from a flat metal sheet. In essence, an AS program is a linear sequence of commands with the mnemonics “MOVE” and “CIRCLE,” which direct the end effector to follow, respectively, straight segments and circular arcs. Consequently, the spatial path of the tool (the cutter in this context) and the corresponding trace left on the processed surface are described by polysegment curves.

Attempting to solve this task with an algorithm that approximates a smooth curve by a polyline leads to a fundamental difficulty. The operands of the MOVE and CIRCLE commands specify the tool’s traversal speed; if the program prescribes motion along a broken line, then regardless of how the speeds on the segments are chosen the manipulator cannot execute such a program exactly as written. From a physical standpoint the reason is straightforward: motion defined by a polyline entails infinite normal (radial) acceleration at the polyline’s vertices. In practice, when such a program is loaded into the controller, the manipulator decelerates and effectively halts each time the tool passes a vertex of the notional polyline on the sheet surface (i.e., along the trajectory trace). For certain cutting processes (e.g., plasma cutting), the temporal accuracy of the trajectory is critical; if the tool speed deviates substantially from the setpoint, the operation may fail or the tool may even be damaged.

This problem is avoided by approximating the smooth curve with a conjugate polysegment rather than with a polyline. It is, of course, desirable to minimize the number of conjugation points along the polysegment that approximates a given smooth planar curve; at the same time, reducing the

number of segments inevitably reduces the achievable approximation accuracy. Taking these two considerations into account, we formulate the optimal planar approximation problem as follows: given a maximum admissible error σ , find a polysegment with the minimum number of segments that approximates the specified curve with an error not exceeding σ .

III. OPTIMAL APPROXIMATION OF A SMOOTH CURVE BY A POLYSEGMENT LINE AND THE ANGULAR CHARACTERISTIC FUNCTION

3.1 Motivation and Related Work

The problem of approximating a planar curve by a sequence of geometric primitives (mutually conjugated circular arcs and straight-line segments) is closely related to the choice of curve representation used in the approximation algorithm. Any such approximation can be regarded as a shape descriptor of the original curve. For a continuous planar curve with two endpoints, one can define such basic attributes as position, orientation, and scale. By applying translation, rotation, and uniform scaling transformations, an infinite number of curves differing only in position, orientation, and scale can be obtained, all sharing the same intrinsic shape.

From this general standpoint, it is desirable that the representation of the curve used in the approximation algorithm separates the description of the curve’s shape from the parameters describing its position and orientation on the plane. The approximation algorithm should then operate directly on the shape descriptor.

In the algorithm presented in this paper for approximating a planar curve by a polysegment curve, we use as a shape descriptor a special function — the angular characteristic function of the curve. As will be shown below, any smooth planar curve can be uniquely associated with a continuous real-valued function of a single variable defined on the unit interval. A smooth curve can be reconstructed from its angular characteristic function and three additional parameters describing position, orientation, and scale (the latter corresponding simply to the curve length).

Originally, the angular characteristic function was used as a shape descriptor in image recognition tasks, specifically for developing an optical system for handwritten symbol recognition. This curve descriptor, invariant under translation, rotation, and scaling, proved to be very effective in digital image analysis. Later it was found that one of the mathematical properties of this construction allows one to design a highly efficient algorithm for planar curve approximation by polysegment lines. In fact, the angular characteristic function of a polysegment curve is a piecewise linear function. Consequently, the problem of optimal approximation of a smooth planar curve by a polysegment curve reduces to the well-known problem of polyline simplification, for which efficient algorithms such as the Ramer–Douglas–Peucker algorithm exist.

The question of selecting an appropriate descriptor capable of representing the shape of a planar curve naturally arises in image processing and recognition problems and has long attracted research attention. The idea of using the curvature distribution along the curve length as such a descriptor was proposed in earlier studies on curvature-based shape signatures [14]. More recently, several works have explored invariant representations of planar curves learned

through machine learning methods [15], as well as curvature-continuous approximations suitable for robotic trajectory planning [16, 17].

In robotics and motion planning, approximating planar trajectories with arcs and line segments remains highly relevant. Paths composed of alternating straight and circular elements exhibit desirable kinematic properties, such as bounded curvature and feasible steering control, as in the classical Dubins path problem [18]. Recent studies further develop this approach, introducing adaptive segmentation and curvature-continuous fitting of planar paths for robotic manipulators and autonomous vehicles [19].

Therefore, our choice of the angular characteristic function as the fundamental shape descriptor is justified by two factors:

- 1) the need for an invariant representation independent of position, orientation, and scaling;
- 2) the direct link between the curve's shape descriptor and its geometric composition from arcs and line segments, which simplifies algorithmic implementation.

The proposed method automatically determines the number and placement of conjugated arcs and straight segments to achieve the required approximation accuracy with minimal computational cost.

3.2 Definition and main properties of the angular characteristic function of a curve

Smooth curves on the plane with two endpoints are considered as smooth mappings of the form $\gamma: I \rightarrow \mathbb{R}^2$, where $I = [0, T]$ is an interval on the real axis. If we interpret the parameter $t \in I$ physically as time, then a plane curve given parametrically as $\gamma(t)$ can be viewed as the trajectory of a point moving on the plane, with the velocity vector defined as $\dot{\gamma}$, and the acceleration vector as $\ddot{\gamma}$. In the special case when $\forall t \in I |\dot{\gamma}(t)| = 1$, the parameter t can be interpreted as the arc length s traversed by the moving point from the starting position. Such a parametrization is called the natural (arc-length) parametrization of the curve. Every smooth curve with two endpoints can therefore be represented in the form (1), where s denotes the natural parameter and L is the total length of the curve.

$$\forall s \in [0, L] \gamma(s) = \gamma(0) + \int_0^s \dot{\gamma}(s) ds \quad (1)$$

Since, under the natural parametrization of the curve, the condition is satisfied, the vector can be represented as (2).

$$\dot{\gamma}(s) = \mathbf{t}(\alpha(s)), \quad (2)$$

where the mapping $\mathbf{t}: S^1 \rightarrow \mathbb{R}^2$ is given by formula (3), which defines the vector components in an orthonormal basis, and the function $\alpha(s)$ determines the shape of the curve.

$$\mathbf{t}(\alpha) = [\cos \alpha, \sin \alpha]^T \quad (3)$$

Differentiating both sides of equation (2) with respect to s yields formula (4) for the second derivative:

$$\frac{d^2}{ds^2} \gamma(s) = \frac{d}{ds} \mathbf{t}(\alpha(s)) = \dot{\alpha}(s) \mathbf{n}(\alpha(s)) \quad (4)$$

where $\mathbf{n}: S^1 \rightarrow \mathbb{R}^2$ is defined by formulas (5):

$$\mathbf{n}(\alpha) = \frac{d}{d\alpha} \mathbf{t}(\alpha) = [-\sin \alpha, \cos \alpha]^T \quad (5)$$

Obviously, for any α the identities $|\mathbf{n}(\alpha)| = 1$ and $(\mathbf{n}(\alpha), \mathbf{t}(\alpha)) = 0$, that is, $\mathbf{n}(\alpha)$ is a unit vector orthogonal to $\mathbf{t}(\alpha)$. Since $\mathbf{t}(\alpha(s))$ is the unit tangent vector to γ at the point $\gamma(s)$, $\mathbf{n}(\alpha(s))$ is the unit normal vector. As we see, the vectors $\mathbf{t}(s)$ and $\mathbf{n}(s)$ (the unit tangent and unit normal to the curve) satisfy the differential equation (6).

$$\frac{d}{ds} \mathbf{t}(s) = k(s) \mathbf{n}(s), \quad (6)$$

where, the real number $k(s)$ is called the signed curvature. It is straightforward to show that $|k(s)| = \frac{1}{R}$, where R is the radius of the circle tangent (the osculating circle) to γ at the point $\gamma(s)$. The sign of $k(s)$ depends on both the orientation of the plane and the orientation of the curve provided by the parametrization. From formulas (4) and (6) it follows that equation (7) holds, which determines the function $\alpha(s)$ up to an additive constant.

$$\forall s \in [0, L] \dot{\alpha}(s) = k(s) \quad (7)$$

It should be noted that formula (7) is directly related to another possible geometric interpretation of the concept of signed curvature. Recall that the angle $\varphi(s)$ between $\mathbf{t}(s)$ and the positive direction of the x -axis is called the turning angle of the plane curve (see Fig. 2). The signed curvature $k(s)$ can also be interpreted as the rate of change of the turning angle with respect to the arc length, which corresponds to the formula $k(s) = \frac{d\varphi}{ds}(s)$.

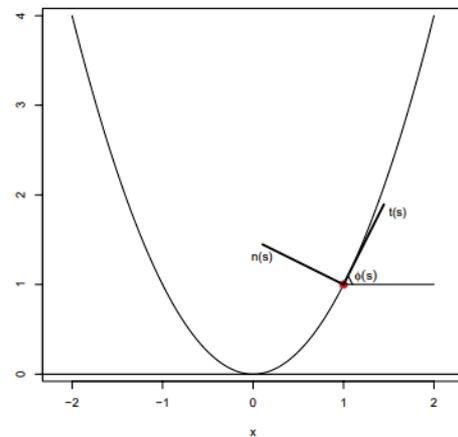


Fig. 2. The positions of $\mathbf{t}(s)$, $\mathbf{n}(s)$ and $\varphi(s)$ relative to an arbitrary red point $\gamma(s)$ on a quadratic curve

As we can see, it is, in principle, possible to define a shape descriptor of a smooth curve as the turning angle by choosing a fixed Cartesian coordinate system on the plane. However, we define the function $\alpha(s)$, which describes the shape of the curve, as the integral of the signed curvature in the form (8).

$$\alpha(s) = \int_0^s k(\tau) d\tau \quad (8)$$

Such a definition is not tied to the choice of a coordinate system on the plane and is invariant with respect to the group of plane transformations generated by translations and

rotations. The function $\alpha(s)$ defined in this way also has a simple geometric interpretation (see Fig. 3).

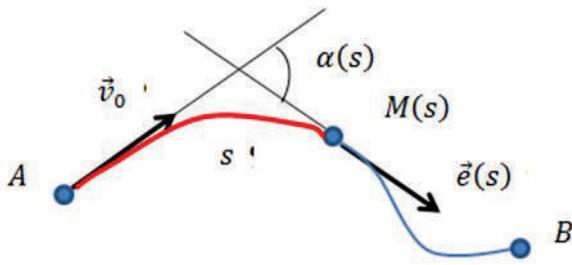


Fig. 3. $\alpha(x)$ represents the angle between the initial tangent vector and the tangent vector at a point along the curve

The function $\alpha(s)$ is defined on the interval $[0, L]$, where L is the length of the curve γ , and it is not invariant under the operation of scaling (uniform stretching of the plane). To obtain a shape descriptor of the curve that is invariant with respect to translations, rotations, and scaling, we define on the interval $I = [0, 1]$ the function $\theta(x)$ by expression (9).

$$\theta(x) = \alpha(x \cdot L) \quad (9)$$

We will call $\theta(x)$ the function of the angular characteristic of the curve γ (or simply the angular characteristic of γ). The angular characteristic function of the curve can be defined analytically by formula (10).

$$\theta(t) = \int_0^{Lt} k(Ls) ds \quad (10)$$

Differentiating both sides of equation (10) gives formula (11), which expresses an obvious but important property of the angular characteristic function.

$$\forall t \in I \dot{\theta}(t) = Lk(Lt) \quad (11)$$

There exist only two types of curves with two endpoints that have constant curvature, namely, a circular arc and a straight-line segment. The angular characteristic functions of these curves have particularly simple forms. Let us consider these two cases separately.

First case, straight-line segment: obviously, the curvature of a straight line is zero at every point of the segment. From (11) and the initial condition $\theta(0) = 0$ we obtain the Cauchy problem for the differential equation $\forall s \in I \dot{\theta}(s) = 0$, whose solution is a constant function $\forall s \in I \theta(s) = 0$.

Second case, circular arc of radius R , and length l . The curvature of a circle is constant and equal in magnitude to $\frac{1}{R}$. In this case, equation (11) corresponds to the differential equation $\dot{\theta}(t) = lkt$, $t \in I$, where $|k| = \frac{1}{R}$. The solution of the Cauchy problem for this equation with the initial condition $\theta = 0$ has the form $\theta(t) = \frac{l}{R}t$. Here, $|\theta(1)| = \alpha$, where $\alpha = \frac{l}{R}$ is the central angle that subtends an arc of length l on the circle.

These two facts, together with the property of the angular characteristic function of a smooth plane curve described below, make it possible to understand the form of the angular

characteristic function of a polysegment line. Let γ be an arbitrary smooth plane curve with two ends at points A and B . Denote by θ the function of the angular characteristic of this curve. Assume that the length of the γ be equal to L . Let us choose an arbitrary point on the curve M , and denote by l_1 the length of the arc AM of the curve γ (in this case, of course, the length of the arc MB will be equal to $L - l_1$). Let us denote by θ_1 the function of the angular characteristic of the curve AM and by θ_2 the function of the angular characteristic of the curve MB . Then the function θ can be expressed through the functions θ_1 and θ_2 , and analytically the relationship between the functions θ , θ_1 and θ_2 is expressed by formula (12).

$$\forall x \in [0, 1] \theta(x) = \begin{cases} \theta_1\left(\frac{Lx}{l_1}\right), & \text{if } x \in [0, \frac{l_1}{L}] \\ \theta_1(1) + \theta_2\left(\frac{(x - \frac{l_1}{L})L}{L - l_1}\right), & \text{if } x \in (\frac{l_1}{L}, 1] \end{cases} \quad (12)$$

Since the characteristic functions of the individual segments of a polysegment curve are linear functions, the graph of the angular characteristic function is a polyline (see Fig. 4).

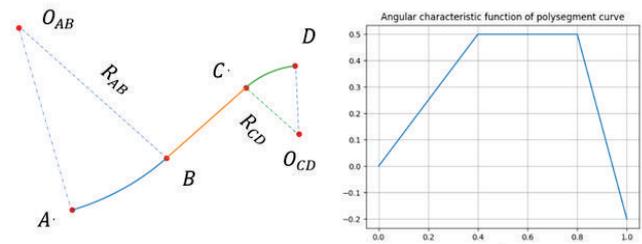


Fig. 4. The polysegment line AD (left) and the graph of its angular characteristic function (right). The graph of the angular characteristic function of the curve AD is a polyline whose three segments correspond to the three segments of AD

As will be shown below, the angular characteristic function of a curve, which describes its shape, together with the data on the curve's position, orientation, and length, contains complete information about the curve and can be used to define it. To demonstrate this, note that from representation (12), taking into account the results obtained above, formula (13) follows, which provides the reconstruction of the curve from its angular characteristic function.

$$\forall s \in [0, L] \gamma(s) = \gamma(0) + \int_0^s \mathbf{t} \left(\theta \left(\frac{\tau}{L} \right) \right) d\tau \quad (13)$$

Naturally, any given angular characteristic function of a curve corresponds to an infinite set of plane curves, and therefore the obtained result can be interpreted in another way. For a given triple (v_0, e_0, l) where vector $v_0 = [v_{0x}, v_{0y}]^T$ defines a position of the point on the plane, $e_0 \in \mathbb{R}^2$ is a constant unit vector, and $l > 0$ is a scalar parameter, an arbitrary angular characteristic function φ uniquely determines a plane curve γ , given by equation (14).

$$\gamma(s) = v_0 + \int_0^l \left[R \left(\varphi \left(\frac{x}{l} \right) \right) e_0 \right] dx, \quad (14)$$

where $R(\alpha)$ is the orthogonal matrix of the two dimension rotation operator, defined by expression (15).

$$R(\alpha) = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \quad (15)$$

Let us denote by θ an arbitrary continuous function defined on the interval $[0,1]$ and satisfying the condition $\theta(0) = 0$. For this function θ and an arbitrary triple (v_0, e_0, l) , the formula (15) uniquely determines a curve on the plane for which θ will be a function of the angular characteristic.

IV. ALGORITHM FOR APPROXIMATING A CONTINUOUS PLANAR CURVE BY A POLYSEGMENT LINE

As shown above, the graph of the angular characteristic function of a polysegment line is a polyline. The main idea of the proposed approximation algorithm is based on this fact and consists in constructing a piecewise-linear approximation $\hat{\theta}$ of the angular characteristic function θ of a given planar curve γ , and then reconstructing, from $\hat{\theta}$ a polysegment line $\hat{\gamma}$, and then reconstructing, from $\hat{\gamma}$ and γ coincide. For the computer implementation of the algorithm, it is convenient to use a discrete representation of continuous planar curves by polylines defined by a sequence of vertices $\{v_1, v_2, \dots, v_N\}$, where $\forall k \in \{1, \dots, n\} v_k \in \mathbb{R}^2$. For a curve given parametrically by the functions $x(t)$ and $y(t)$, the polyline representing the curve is obtained by discretizing these functions, with the coordinates of the polyline vertices defined as $v_k = [x_k, y_k]^T$. As will be shown below, the definition of the angular characteristic function naturally extends to the case of polylines. For given polyline $\{v_1, v_2, \dots, v_n\}$ we denote $\alpha_k = \begin{cases} 0 & \text{if } k = 1 \\ \angle(\tilde{e}_k, \tilde{e}_{k-1}), & \text{otherwise} \end{cases}$. Let $\theta_k = \sum_{i=1}^k \alpha_k$ and we define the sequence $\{s_k\}$ by the formulas $s_k = \begin{cases} 0, & \text{if } k = 1 \\ \frac{\sum_{j=1}^k |\tilde{e}_j|}{L}, & \text{otherwise} \end{cases}$, where $L = \sum_{j=1}^{n-1} |\tilde{e}_j|$ is a total length of the polyline. Then the angular characteristic function $\theta(x)$ is a piecewise constant function defined as $\theta(x) = \theta_k$ if $x \in [s_k, s_{k+1})$ (see Fig. 5).

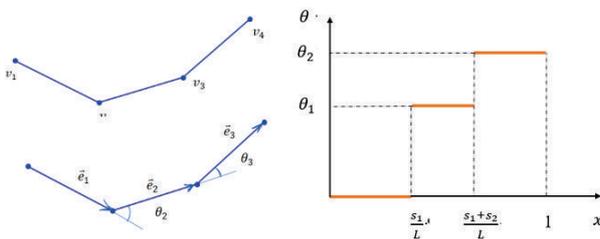


Fig. 5. The angular characteristic function of a polyline is a piecewise constant function

As will become evident below, working with a discretely sampled angular characteristic function is much more convenient than with a piecewise constant one. Therefore, in the algorithm implementation, we discretized the computed angular characteristic functions, and throughout the

following discussion we will assume that the angular characteristic function is given as a list of samples. An example of the graph of an angular characteristic function computed in this way for a synthetic example is shown in Fig. 6.

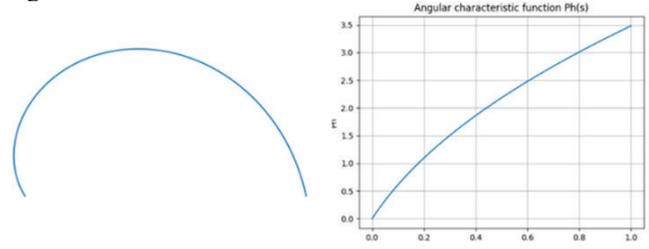


Fig. 6. A plane curve defined by the parametric equations $x(t) = -(1+2t)\cos t$ and $y(t) = (1+2t)\sin t$ (left) and the graph of its angular characteristic function (right)

The problem of optimal piecewise-linear approximation of a function given by discrete samples reduces to the problem of optimal polyline decimation. For approximating the angular characteristic function, we used the Ramer–Douglas–Peucker algorithm (also known as the Douglas–Peucker or iterative end-point fit algorithm). This algorithm simplifies a curve composed of line segments to a similar curve with fewer points.

An important property of the Ramer–Douglas–Peucker algorithm is its ability to automatically select the optimal subset of vertices from the original polyline to be retained during decimation, thereby ensuring the user-defined approximation accuracy.

Fig. 7 shows an example of applying the Ramer–Douglas–Peucker algorithm with different values of the maximum allowable approximation error parameter.

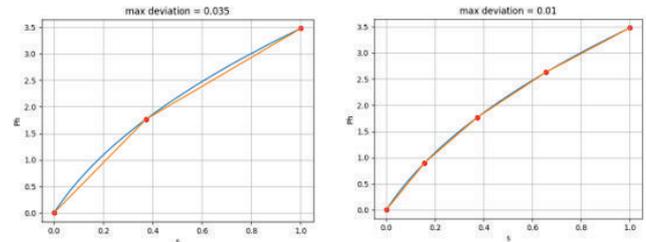


Fig. 7 Application of the Ramer–Douglas–Peucker algorithm for constructing a piecewise-linear approximation of the angular characteristic function

To construct a polysegment line approximating a given continuous planar curve, we need an algorithm that reconstructs a polysegment line from its piecewise-linear angular characteristic function. Obviously, the graph of a piecewise-linear function $\theta(t)$, defined on the interval $I = [0,1]$ is a polyline, and such a function is completely determined by specifying the vertices of this polyline. Each vertex v of the polyline is described by a coordinate pair (t, φ) , where $t \in I$ and $\varphi = \theta(t)$. We interpret this pair as the coordinates of a vector in the Cartesian basis, i.e. $v = [t, \varphi]^T \in \mathbb{R}^2$. We will assume that the sequence of vertices $\{v_1, v_2, \dots, v_N\}$ defining the piecewise-linear angular characteristic function $\theta(t)$ is ordered in such a way that for any two consecutive vertices $v_k = [t_k, \varphi_k]^T$ and $v_{k+1} = [t_{k+1}, \varphi_{k+1}]^T$ the condition $t_k < t_{k+1}$ is satisfied. At the

same time, the sequence of vertices $\{v_1, v_2, \dots, v_N\}$ starts with the zero vector $v_1 = [0,0]^T$. Let us denote by $d_k = v_{k+1} - v_k = [\Delta t_k, \Delta \varphi_k]^T$, where $\Delta t_k = t_{k+1} - t_k$ and $\Delta \varphi_k = \varphi_{k+1} - \varphi_k$ is a vector the one corresponding to the k -y th segment of the polyline. $\{v_1, v_2, \dots, v_N\}$. We associate with the segment d_k of the piecewise-linear angular characteristic function a vector $e_k = \Delta t_k R_{\varphi_k}(q_k)$, where R_α is the linear rotation operator through the angle α , and the vector q_k is defined by expression (16).

$$q_k = \begin{cases} \frac{1}{\Delta \varphi_k} \cdot [\sin(\Delta \varphi_k), 1 - \cos(\Delta \varphi_k)]^T, & \text{if } \Delta \varphi_k \neq 0 \\ [1,0]^T. & \text{otherwise} \end{cases} \quad (16)$$

It is not difficult to show that the polyline defined by the sequence of vertices $\{p_1, p_2, \dots, p_N\}$, where $p_1 = [0,0]^T$ and the positions of the remaining vertices are given by the recurrence relation $p_{k+1} = p_k + e_k$ corresponds to a unit-length polysegment line for which $\theta(t)$ is the angular characteristic function. The vertices $\{p_1, p_2, \dots, p_N\}$ lie on this polysegment line and correspond to the junction points of its segments. Note that the edges e_k , of the polyline, for which $\Delta \varphi_k \neq 0$ correspond to the segments of the polysegment curve that are circular arcs of radius $R_k = \frac{\Delta t_k}{\Delta \varphi_k}$, while the segments corresponding to straight-line portions coincide with the respective edges e_k . The problem of selecting the translation vector, rotation angle, and scaling factor that transform the constructed polysegment line into a planar curve whose endpoints coincide with those of the original curve is completely straightforward. With a reasonable choice of the tolerance parameter in the Ramer–Douglas–Peucker algorithm, the proposed method makes it possible to achieve high-accuracy approximation of a planar curve by a polysegment line, as illustrated by the example shown in Fig. 8.

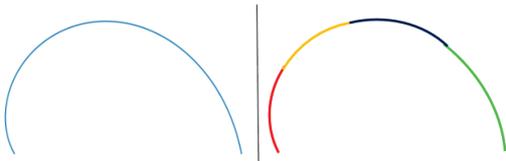


Fig. 8. Result of applying the polysegment approximation algorithm

The reconstructed polysegment closely tracks the reference curve while using few junctions; the maximum deviation remains within the prescribed tolerance, confirming accurate and curvature-consistent approximation suitable for direct MOVE/CIRCLE program generation.

V. CONCLUSION

This paper proposed an efficient algorithm for approximating planar curves by conjugated circular arcs and straight-line segments, based on an invariant representation of the curve known as the angular characteristic function. The approach enables automatic segmentation of digital curves into a minimal number of geometrically consistent elements while preserving smooth curvature continuity. The use of the Ramer–Douglas–Peucker algorithm provides an adaptive control of accuracy and computational cost, ensuring compact and precise curve reconstruction. The resulting

polysegment curves are directly applicable to robotic programming languages such as AS, enabling automatic generation of motion trajectories for surface processing and coating tasks. The simplicity, invariance properties, and low computational requirements of the proposed method make it well suited for both image analysis and robotic trajectory planning. Future work will extend the method to 3D curves and embed dynamic constraints for real-time robotic manufacturing.

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A Study on Predicting Term Weighting Models with Query Performance Predictors to Enhance Information Retrieval Effectiveness

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Abstract—Information retrieval systems often exhibit variability in effectiveness across queries and retrieval models. This study investigates the use of pre-retrieval query performance predictors to guide per-query prediction of term weighting models. A prediction-based method (PBM) is employed using a K-Nearest Neighbors (KNN) to predict between BM25 and DFRee term weighting models based on features derived from query performance predictors. Experiments are conducted on standard TREC datasets, which are CW09B, CW12B, and GOV2, and retrieval effectiveness is evaluated using nDCG@20. Results demonstrate that PBM consistently outperforms the baseline models. It achieves statistically significant improvements in average effectiveness and enhanced robustness across queries. Per-query analyses show that PBM accurately predicts the more effective model between term weighting models. These findings indicate that query-level model prediction based on query performance predictors can substantially improve IR performance.

Index Terms—index term weighting, query performance prediction, information retrieval

I. INTRODUCTION

Information retrieval (IR) systems are designed to address users' information needs. Ideally, the response of an IR system should fully satisfy those needs. Systems that consistently succeed in meeting users' diverse information requirements are regarded as robust. Such systems distribute their effectiveness evenly across all queries, rather than a marginal performance increment on only a subset [1].

An IR system typically consists of three sub-components for addressing users' information needs: preprocessing, term–document matching, and re-ranking. Among these, the term–document matching phase serves as the core of the system. Although the other components are relatively optional, they significantly influence the overall performance of an IR system [2], [3], at least as much as the core component itself [4]. From this perspective, the configurations chosen for each component can substantially affect the retrieval of documents for a given set of queries. Consequently, in practical applications, IR systems often fail to satisfy all user information needs at a desirable level [5].

The literature has a long history of improving the effectiveness of IR systems across all sub-components. For instance,

employing stemming in the pre-processing phase is a typical and substantial application, as stemming aims at alleviating the mismatching problem between query and document terms. Accordingly, both, rule-based [6]–[8] and statistical stemming methods [9], [10] have been widely integrated into IR systems [2], [11].

Term weighting models, as a core sub-component of the IR systems, have a central role in identifying relevant documents within a corpus. Because of its importance, a wide range of models have been developed and presented in the literature. BM25 [12], DFRee [13], and DFIC [14] are some example methods from the extensive literature. Each method relies on a distinct probability distribution for modeling the query term frequencies. BM25 employs a Two-Poisson distribution while DFRee uses a Hypergeometric distribution. On the other hand, DFIC utilizes the Empirical distribution. Besides these term weighting models, many other models rely on different kinds of distributions and techniques.

Having relevant documents ranked higher makes it easier for users to access the information they need more quickly. The third phase re-ranks the documents retrieved by the index term weighting model to promote documents considered more relevant to higher positions in the ranked list. Metrics such as Normalized Discounted Cumulative Gain (nDCG) [15], [16] explicitly account for ranking positions when evaluating retrieval effectiveness. Similar to previous phases, multiple methods have been explored for re-ranking. Learning-to-rank method employs machine learning methods to re-rank retrieved documents for a given query [17]. On this account, selected or used features based on query-independent or query-dependent gain importance for this phase. The proposed methods for re-ranking in the literature [17]–[19] inherently affect the measured retrieval performance.

The capabilities of large language models (LLMs) and pretrained language models (PLMs) in capturing semantic meaning have also influenced all sub-components of information retrieval. On this account, several retrievers such as DeepCT [20], DeepImpact [21], uniCOIL [22], and SPLADE [23] are introduced to retrieve documents for a given query from the corpus, while re-rankers such as MonoT5 and DuoT5

[24], and RankT5 [25] have been proposed for post-retrieval ranking in the literature. However, the computational cost of LLMs and PLMs has restricted their deployment to relatively small corpora compared to web-scale datasets in IR experiments. Consequently, an IR system includes multiple sub-components, and each sub-component affects the retrieval performance for each query differently. While some queries benefit from a particular system configuration, the same setup may hinder effectiveness for other queries.

In this study, an experiment is conducted to predict the appropriate term weighting model using several pre-retrieval query performance predictors. The prediction relies on the K-Nearest Neighbors (KNN) and aims at determining which of the two term weighting models yields more effective results. By employing two system setups (one for each term weighting model), the usefulness of query performance predictors in guiding model selection is examined. Furthermore, the retrieval effectiveness of this prediction-based method (PBM) is analyzed on a per-query basis.

II. EXPERIMENTS

The experiments are conducted on Apache Lucene, an open-source search engine platform. Although its usage in the industry is well established, its adoption in academic research has also become increasingly widespread. For the experiments, the Web documents are stripped of the HTML tags to obtain textual content and then indexed in Lucene for search and retrieval. Standard tokenizer and lower case filtering are applied to the textual content without stemming during the indexing process.

A. Datasets

The ClueWeb09 collection consists of approximately 1 billion web documents gathered in January and February 2009. The collection's Category B subset contains approximately 50 million English web pages. The subset was used in TREC Web Tracks from 2009 to 2012 (CW09B). The ClueWeb12 comprises approximately 733 million English web documents, gathered between 10 February and 10 May 2012. A uniformly extracted sample of 7% of the collection is named Category B13. The subset collection was used in the TREC Web Tasks from 2013 to 2016 (CW12B). The GOV2 collection [26] involves approximately 25 million web documents. These documents were gathered from the .gov domain. The TREC Terabyte Tracks 2004–2006 (GOV2) study was conducted using this collection. The experiments are carried out on standard TREC datasets with their associated tracks. The numbers of queries in these tracks are listed in Table I

B. Query Performance Predictors

The variability in retrieval effectiveness across both queries and systems has motivated research into query performance prediction [27]. The objective is to estimate the quality of search results produced by a specified retrieval system for a given query without relying on human relevance judgments.

TABLE I
THIS LISTS THE COLLECTIONS, THE NUMBER OF QUERIES IN THE TRACKS, AND THE ABBREVIATIONS USED IN THE EXPERIMENTS.

Collection	Track	Abbr. in Study	# queries
CW09B	Web 2009, 2010, 2011 & 2012	CW09B	197
CW12B	Web 2013 & 2014 Tasks 2015 & 2016	CW12B	185
GOV2	Terabyte 2004, 2005 & 2006	GOV2	149

Accurate prediction would enable information retrieval systems to better manage difficult queries and mitigate performance fluctuation. Furthermore, identifying the most effective retrieval strategy on a per-query basis has the potential to substantially improve overall effectiveness.

The potential of query performance prediction for improving IR effectiveness has motivated extensive research into diverse prediction methods. These approaches are typically classified into pre-retrieval and post-retrieval methods. Pre-retrieval methods estimate search result quality before retrieval. It relies solely on the raw query and term statistics available at indexing time. In contrast, post-retrieval methods leverage not only the query and term statistics but also features derived from the retrieved results. In this study, experiments are performed on only pre-retrieval predictors since using post-retrieval predictors requires multiple runs of queries on the IR systems. In this context, the employed predictors for the KNN are listed:

- **Inverse document frequency (idf)**: Queries are usually consist of multiple terms. Mean, variance, and maximum *idf* values of query terms are produced for the feature set. The used formula: $idf = \ln(N/df(t))$, where N and $df(t)$ refer to the number of documents in the collection and the document frequency of the term t
- **Query Scope** [28]: Represents the percentage of documents in the corpus that include at least one query term. The equation: $\omega = -\log(n_Q/N)$, where n_Q refers to the number of documents that include at least one query term.
- **Gamma** [28]: Captures the distribution of information content across the component terms of a query. The equation: $\gamma = idf_{max}/idf_{min}$
- **Pointwise Mutual Information (PMI)** [29]: PMI scores for each query term pairs. Mean and maximum *PMI* values of query term pairs are produced for the feature set. The equation:

$$PMI(t_1, t_2) = \log \frac{Pr(t_1, t_2 | D)}{Pr(t_1 | D) \cdot Pr(t_2 | D)}$$

- **Simplified Clarity Score (SCS)** [30]: Quantifies query specificity by measuring the Kullback–Leibler divergence between the query language model and the collection language model.

TABLE II
AVERAGE RETRIEVAL RESULTS OF IR SYSTEMS IN THE METRIC
NDCG@20.

	CW09B	CW12B	GOV2
BM25	0.1606	0.0781	0.3486
DFRee	0.1596	0.0891	0.3552
PBM	0.1651^D	0.0926^B	0.3601^B

The equation:

$$SCS(q) = \sum_{t \in q} Pr(t | q) \log \left(\frac{Pr(t | q)}{Pr(t | D)} \right)$$

- **Contribution of a term to the total inertia (CTI)** [31]: Total inertia reflects the overall magnitude of squared deviations from independence. Mean, variance, and maximum *CTI* values of query terms are produced for the feature set.

The equation:

$$CTI = \frac{1}{N} \sum_{j=1}^c \frac{(tf_{ij} - e_{ij})^2}{e_{ij}}$$

where i refers to term number and j refers to document number.

- **Skewness and Kurtosis:** Skewness and kurtosis of the frequency distribution for a query term. Mean and variance *Skewness* and *Kurtosis* values of query terms are produced for the feature set separately.
- **Collection Query Similarity (SCQ)** [32]: Measure the query similarity to the collection. Mean, variance, and maximum *SCQ* values of query terms are produced for the feature set.

The equation: $SCQ(t) = (1 + \log(tf(t, D))) \cdot idf(t)$

C. Experimental Setup

The prediction decides which term weighting model should be applied to the information retrieval system for a given query. For this purpose, DFRee [13] and BM25 [12] are selected as baseline term weighting models. These are well-known and widely used models in literature and practical applications. Retrieval effectiveness is evaluated using nDCG at the top 20 documents (nDCG@20). A KNN classifier is employed to perform the prediction using extracted pre-retrieval query performance predictors as input features. Each query feature set is assigned one of three labels: 0 (BM25), 1 (DFRee), or 2 (equality). Specifically, if the nDCG@20 score of BM25 is higher than that of DFRee for a given query, label 0 is assigned. Conversely, if the DFRee score is higher, label 1 is assigned. In cases where the scores are equal, label 2 is assigned.

D. Results

Table II lists the average nDCG@20 scores of the term weighting models across the query collection datasets. The applied classifier is denoted as PBM, which refers to the prediction-based method. The bold scores indicate the higher

scores. The superscripts *B* and *D* indicate that the average retrieval performance of the PBM is statistically significant compared to DFRee and BM25, respectively, at the 0.05 significance level. According to the table results, KNN-based prediction of the term weighting model using query performance predictors produces the highest effectiveness scores. Furthermore, the produced result for CW09B is statistically significantly higher than that produced by DFRee. Also, a similar situation is observed in the CW12B and GOV2 query collection datasets. The produced scores for these datasets are statistically significantly higher than BM25.

Fig. 1 illustrates the per-query comparisons of the PBM against DFRee and BM25 for each dataset. The bars in the upper-right region represent the queries for which PBM achieves higher nDCG@20 scores than the corresponding baseline model. On the other hand, the bars in the lower-left region indicate queries where PBM performs worse. The length of the bar reflects the magnitude of these differences. In the figures, the area covered by the upper-right bars exceeds that of the lower-left bars. It can be inferred from the figures that PBM is accurate in prediction and especially on the queries that have marginal differences between term weighting models.

Fig. 2 also compares the per-query retrieval scores sorted in ascending order for each term weighting model. Each sub-figure corresponds to a specific query collection. Here, the blue, red, and yellow lines indicate the BM25, DFRee, and PBM models. The line for the PBM model usually appears above the other lines of models. This shows that the PBM usually produces more robust results than others, and an increment in average performance is usually distributed across the queries.

III. DISCUSSION AND CONCLUSIONS

This study investigated the use of pre-retrieval query performance predictors to guide the selection of term weighting models in information retrieval systems. The prediction-based method (PBM), leveraging a KNN classification, dynamically selects a term weighting model between BM25 and DFRee for each query. Experimental results on standard TREC datasets (CW09B, CW12B, and GOV2) demonstrated that PBM has achieved higher nDCG@20 scores compared to either baseline model. The improvements have been statistically significant in multiple cases, and this highlights the effectiveness of per-query model selection.

Per-query analyses further revealed that PBM not only improved average retrieval effectiveness but also enhanced robustness across queries. Figures 1 and 2 show that PBM frequently outperformed the baselines, particularly for queries with marginal performance score differences between models, and that performance gains are broadly distributed rather than concentrated on a few queries. These findings indicate that query performance predictors can successfully identify situations in which a specific term weighting model is likely to be more effective. This allows IR systems to mitigate performance variability across queries.

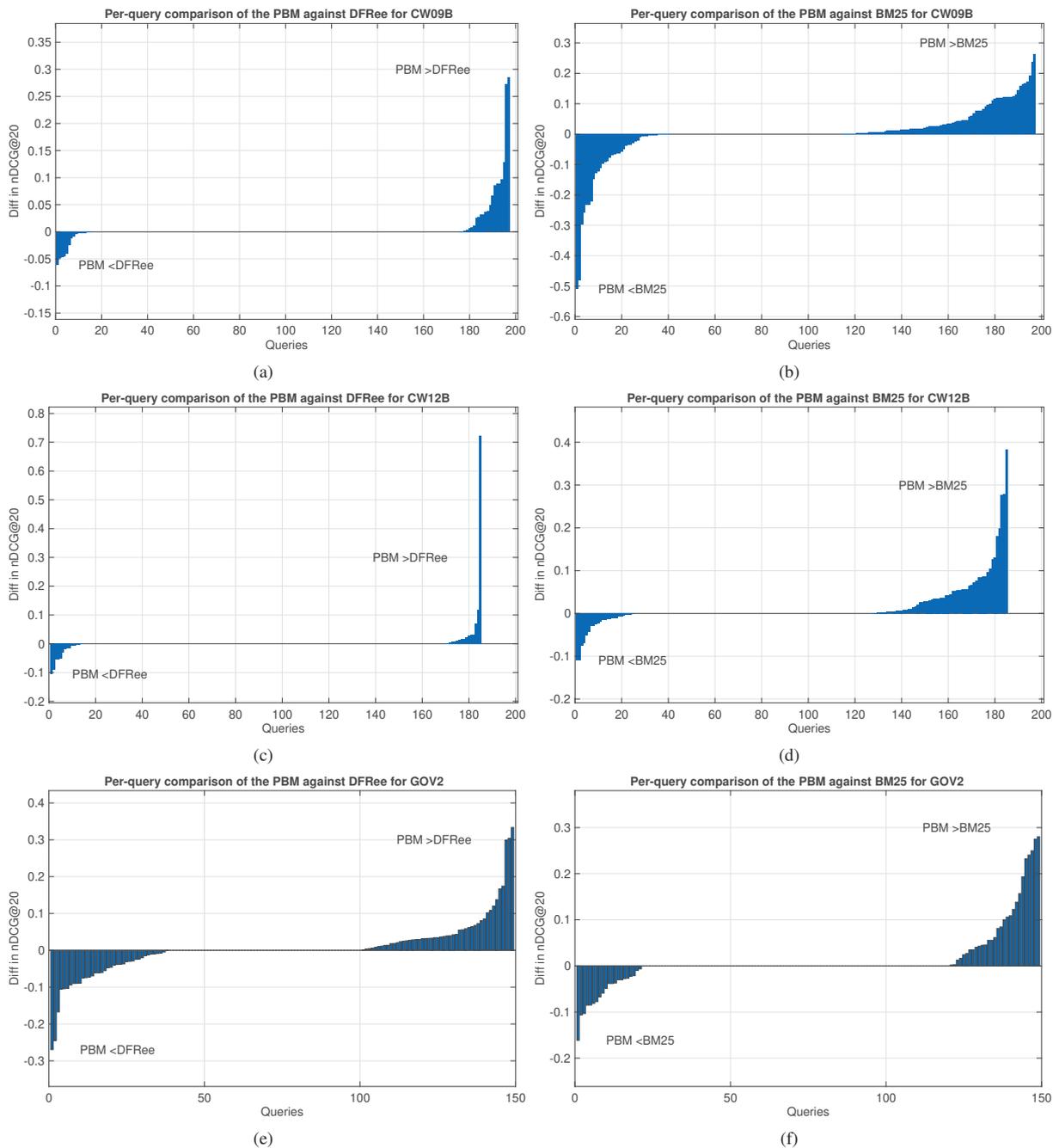


Fig. 1. Visual comparison of the PBM against base term weighting models is presented. The right upper bars represent the number of queries and performance gain with the PBM. The left bottom bars represent the number of queries and performance loss with the PBM.

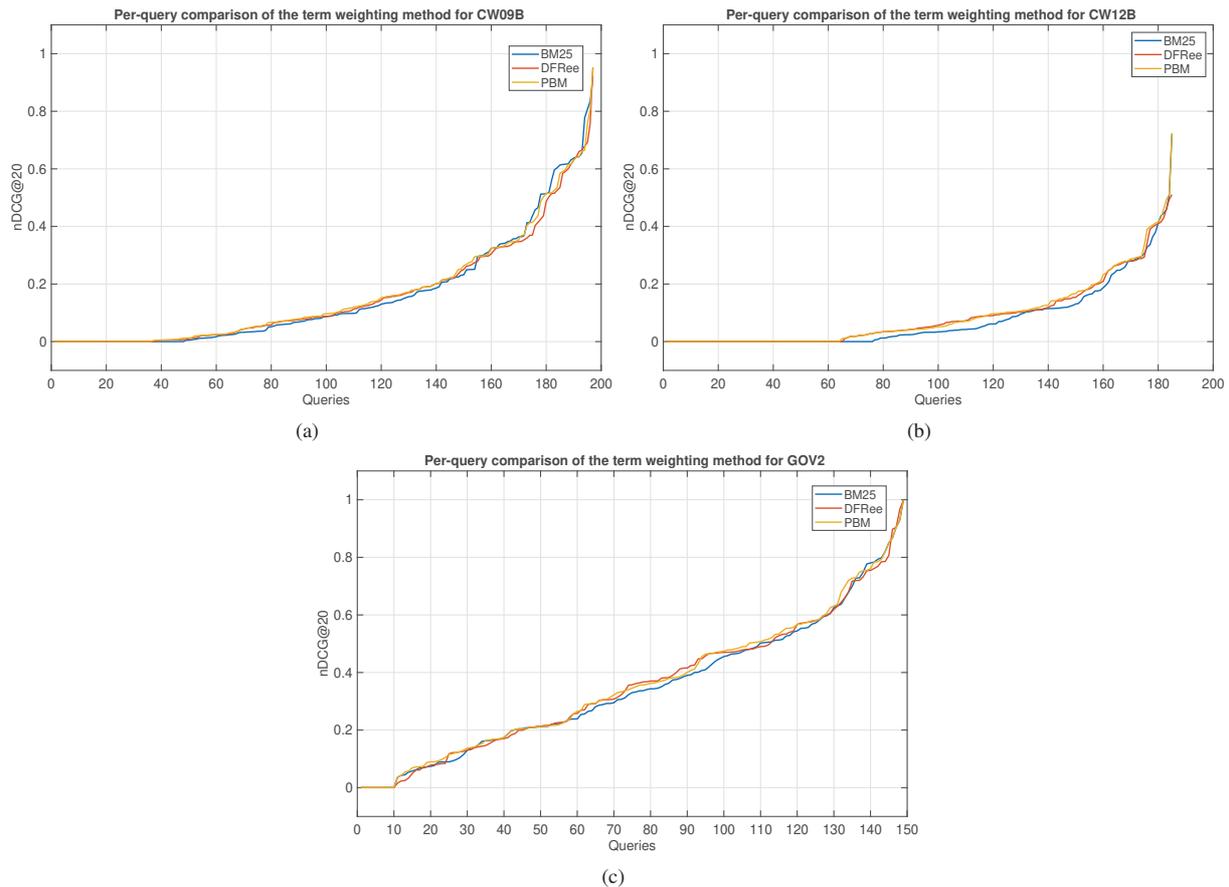


Fig. 2. Per-query performance comparisons of term weighting models and PBM according to CW09B, CW12B, and GOV2.

Despite its effectiveness, this study has several limitations. Only two term weighting models (BM25 and DFRee) are considered, which limits the generalizability of the prediction-based method to other models; however, they are more widely used term weighting models. Although there are other metrics, the experiments focus on $nDCG@20$ as the evaluation metric, which is a more suitable metric for evaluating web information retrieval.

In conclusion, the prediction-based method demonstrates that pre-retrieval query performance predictors can be effectively used to select term weighting models on a per-query basis. This usually results in significant improvements in both average effectiveness and robustness. These findings provide a promising direction for adaptive IR systems to the specific characteristics of individual queries.

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Web-Based VR Application Development: Opportunities and Challenges

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Abstract—Virtual reality (VR) technology has rapidly matured, yet traditional desktop-based VR systems remain constrained by hardware limitations and platform dependencies. This paper explores the evaluation of web-based VR solutions, emphasizing cross-platform technologies such as WebXR, WebGL, WebAssembly, and WebGPU. Through a detailed case study of a VR game developed using Wonderland Engine, it was demonstrated how modern browser APIs deliver immersive VR experiences efficiently. The study outlines key technical challenges, including optimization strategies, user experience (UX) design considerations, and trade-offs compared to native VR development platforms.

Index Terms—WebXR, WebAssembly, WebGL, WebGPU, VR optimization, Wonderland Engine, browser-based virtual reality.

I. INTRODUCTION

Traditional VR development primarily utilizes specialized hardware and native engines such as Unity and Unreal Engine, limiting accessibility and scalability. Web-based VR, facilitated by technologies like WebXR and WebGL, significantly lowers entry barriers, providing broad, cross-platform access without additional installations. This paper investigates these technologies, highlighting their potential and challenges.

The technologies discussed in this paper form a layered and complementary ecosystem rather than competing solutions. WebXR acts as the high-level interface for accessing VR and AR devices and handling spatial tracking. WebGL provides the graphics rendering layer that WebXR relies on for displaying 3D content inside the browser. WebGPU is an emerging next-generation graphics API that extends or replaces WebGL with lower-level GPU access and improved performance. WebAssembly (Wasm) operates alongside JavaScript, enabling near-native execution speed for compute-intensive parts of the VR application. In this hierarchy, WebXR sits on top of WebGL or WebGPU for rendering, while WebAssembly accelerates logic and physics computations under the same framework.

Web-based VR engines offer rapid deployment and reduced development overhead. However, they lag behind Unity or Unreal Engines in rendering fidelity and advanced simulation capabilities. Yet, their browser-native nature avoids platform-specific builds and installers.

WebGL enables browsers to render real-time 3D graphics efficiently, while WebXR provides a device-agnostic interface to immersive displays and input tracking. Together, these technologies offer a viable, lightweight alternative to traditional native VR engines.

WebAssembly (Wasm) allows compiled code to run at near-native speeds within web browsers. Coupled with WebXR and advanced rendering libraries, such as Wonderland Engine, WebAssembly supports complex, performant simulations. SIMD extensions further optimize critical matrix and physics computations.

This paper investigates the issues connected to the WebVR development. A critical question for web-based VR is performance across different platforms. The second question is the program's ease of use and input latency. The third issue is loading and network speed.

II. METHODS

The method applied in this study was the development of a sample application demonstrating the use of web-based VR technologies. A prototype was created using Wonderland Engine and deployed with browser-native tools to evaluate cross-platform performance and usability. The sample application was a 3D reinterpretation of the Chrome Dino game built in Wonderland Engine. The virtual environment consisted of a desert track populated with interactive obstacles. The player collects points by dodging obstacles using VR headsets and controllers.

The project architecture included:

- Navigation: Continuous forward movement with lateral interaction.
- Scoring: Real-time score updates rendered in 3D.
- Feedback: Collision triggers providing visual and sound responses.

The development used Docker for platform independence and GitHub Actions for automated deployment. A Tampermonkey userscript allowed runtime parameter injection without modifying the core application. This approach provides similar flexibility to Unity's runtime scripting or developer console, where variables and behaviors can be adjusted dynamically

without recompiling the project. In both cases, it enables rapid iteration and testing of new parameters directly within the deployed environment.

During the development of the sample application, it was aimed to highlight not only the game logic and implementation but also to demonstrate the integration of modern development practices. Version control, particularly GitHub-based work-flows, was given a central role, which is essential in modern projects involving multiple developers. While version control is indispensable, the use of Docker and CI/CD pipelines can be considered optional. Nevertheless, these technologies greatly contribute to the structure, scalability, and maintainability of the project.

A. Application Structure

1) *Navigation*: The player moves in a VR environment and must avoid obstacles. Currently, movement is triggered by pressing one of the controller's triggers.

2) *Scoring*: Players earn points by successfully avoiding obstacles. Although a scoring system is implemented, single-player mode is currently supported.

3) *Simple Interactions*: User interactions are handled via VR controllers or keyboard. The game can be played both with and without a VR headset.

The application comprises not only game elements but also logical modules that manage VR interactions, camera motion, and user feedback. Each object in the scene has components such as a "Jump Handler" or "Score Counter." A diagram of the scene's structure would be helpful to illustrate the relationships between the player, obstacles, ground, and control UI. Further improvements could involve error-handling for missing assets or unsupported devices.

The game is a VR version of the classic Chrome Dino game, where players navigate a VR environment to dodge obstacles. It is available on the itch.io platform for anyone with a compatible browser. The application is available.[15]

Docker is an open-source platform that allows applications to be packaged and run in isolated containers. These containers include all necessary files, libraries, and dependencies, making the software independent of the host system.

Docker uses a shared OS kernel to manage resources efficiently. Containers are created from image files defined in a Dockerfile. This approach also applies to web-based VR applications, enabling reproducible environments regardless of the development machine.

In a WebXR project, it is practical to containerize the backend API, static asset server, and build pipeline using

Docker Compose. These components can be started in sync, streamlining deployment. Isolation enhances security, and CI/CD pipelines can automate updates.

Docker image for this application was also created, based on Ubuntu Linux. It installs required dependencies (e.g., NPM), downloads the application from GitHub, and automatically builds a release.

B. Browser-Based Development with GitHub and VS Code

Web-based technologies allow full development in the browser. Developers can upload their codebase to GitHub and use the web version of Visual Studio Code (VS Code) directly.

By changing the ".com" in a GitHub repository URL to ".dev", VS Code opens in the browser:

Original:<https://github.com/TheOnlyCoffeeman/DinoGameR>

Browser:<https://github.dev/TheOnlyCoffeeman/DinoGameR>

This setup supports editing, commits, pulls, and pushes as if working locally. It is ideal for WebXR development, reducing environment setup and increasing flexibility.

Platforms like GitHub Codespaces or Gitpod offer full-featured cloud environments. The web-based VS Code provides an integrated terminal, editor, and version control interface. This approach allows mobile editing, quick bug fixes, or CI oversight without needing local tools.

C. Project Structure and Key Files

- **js/**: JavaScript files for game logic and interactions.
- **models/**: 3D models (e.g., dinosaurs) in .glb/.gltf format.
- **static/sfx/**: Sound effects for events like jumping or collisions.
- **test/**: Scripts and files for manual or automated testing.
- **DinoGame.wlp**: Wonderland Engine project file with scene configurations.
- **README.md**: Project description, usage instructions, and metadata.
- **Sources.txt**: References to models, sounds, or external assets.
- **package.json, package-lock.json**: Node.js dependencies and metadata.

D. Automated Build with GitHub Actions

Automation is achieved with a `build.yaml` file placed in `.github/workflows`. This defines steps for GitHub Actions to perform after code is pushed:

- 1) Code is pushed to GitHub.
- 2) GitHub Actions triggers the workflow.
- 3) Docker-based build installs dependencies and ensures consistency.
- 4) A release is automatically published on GitHub.

This automation is highly beneficial for web-based VR projects, reducing release time and improving transparency.

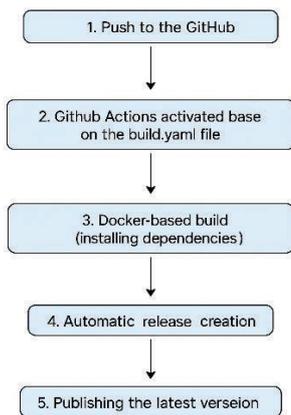


Figure 1. Automated build workflow

E. Experimental Tampermonkey Script

To showcase the sample app's usability, a Tampermonkey script was created that adds a link to the VR game on Obuda University's AMK website.

Tampermonkey customizes web-pages by injecting new elements or altering DOM content. The script activates only on `amk.uni-obuda.hu`, listening for the `DOMContentLoaded` event before modifying the DOM. It inserts a new `<a>` element pointing to the VR game (e.g., GitHub Pages URL), using `grant none` for secure execution.



Figure 2. Tampermonkey script in use, demonstrating the experimental injection of a VR application link into the Obuda University website to simulate its future static integration.

The purpose of this modification was to demonstrate how an academic prototype can be integrated dynamically into an existing institutional webpage without modifying server-side code. By inserting the link locally through Tampermonkey, the approach remains non-intrusive and reversible while showcasing the potential of browser-side customization for rapid demonstration and educational outreach. This Tampermonkey integration was only an experimental method used to simulate the connection of the application with the Obuda University website. In a persistent implementation, the same functionality would be realized by embedding the link or script statically into the website's source code rather than injecting it through a browser extension. The game was tested on a Pico 4 headset, a desktop PC, and a mid-range Android smartphone using Chrome. The desktop configuration featured an Intel Core i7 CPU, 16 GB RAM, and an NVIDIA RTX 3060 GPU, running Windows 11 with the latest Chromium build (116.0.5793.0). The Pico 4 standalone headset operated on the Snapdragon XR2 platform, while the smartphone used a

Snapdragon 778G processor with 8 GB RAM. Additionally, a tablet test (Samsung Galaxy Tab S8) was conducted to evaluate touch-based navigation and browser compatibility in larger-screen mobile environments.

III. RESULTS AND DISCUSSION

To ensure reproducibility and clarity of performance evaluation, several measurement metrics were defined explicitly. The Lighthouse score was used as an automated web-performance metric generated by Google's Lighthouse tool, measuring page load efficiency, rendering performance, and accessibility on a 0–100 scale. User experience (UX) was evaluated subjectively based on participants' responses to a standardized 1–10 scale questionnaire assessing visual smoothness, responsiveness, and ease of interaction. Input latency was quantified by analyzing recorded test footage frame by frame, measuring the elapsed time between input activation (e.g., trigger press) and the corresponding on-screen movement. All performance tests were conducted at a resolution of 1920×1080 pixels on desktop and 1832×1920 per eye on the Pico 4 headset. These definitions ensure consistent interpretation of the metrics presented in this section.

The first question is the performance during software execution.

A. Technical Performance

Key metrics: FPS, response time, memory usage, CPU load.

Table 1. CPU USAGE MEASUREMENTS

Device	Avg. CPU Load	Frame Render Time
Desktop PC	24%	7.1 ms
Pico 4	46%	12.8 ms
Android	58%	19.3 ms
Phone/Tablet		

The desktop performed best with stable 90 FPS, 2.1s load time, and low CPU usage. Pico 4 achieved 72 FPS, with longer load times due to hardware limits. Android had the greatest challenges (45 FPS average), limited by its mobile GPU.

The limitation is caused by the inherent constraints of mobile GPUs and the architectural overhead introduced by web-based execution through Wonderland Engine. Although the engine compiles to WebAssembly, allowing near native performance, the application still runs within the browser's sandboxed environment, where rendering operations are mediated by WebGL or WebXR APIs rather than direct native GPU access. Mobile GPUs, optimized for low power consumption and thermal stability, are unable to sustain the same shader complexity, texture resolution, and draw call volume achievable on desktop class hardware. This limitation is further amplified by browser level resource management, thermal throttling, and memory allocation

restrictions, which prevent full utilization of GPU resources. Consequently, while Wonderland Engine effectively minimizes overhead through its WebAssembly runtime, web-based VR applications on mobile platforms remain constrained by hardware efficiency trade offs and browser API abstraction layers.

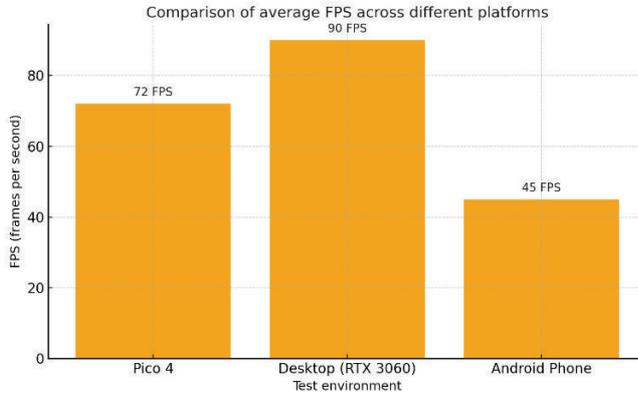


Figure 3. Average FPS comparison across different systems, illustrating performance variations between desktop, standalone VR headset, and mobile devices.

B. Interactions

User navigation time (to first obstacle) and input latency (e.g., jump response time) were measured. Desktop offered excellent UX with low latency and high refresh rates (rated 9/10). Pico 4 performed well, though controller delay was noticeable (42 ms). Mobile had higher input lag (63 ms), leading to a lower experience rating (6.8/10).

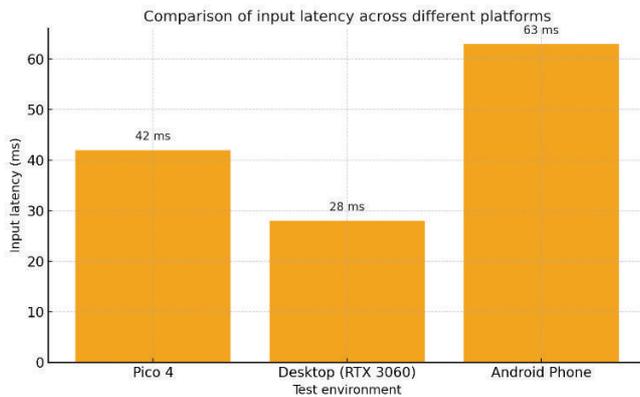


Figure 4. Input latency measurements showing the response delay between user actions and visual feedback across desktop, VR headset, and mobile platforms.

C. Web Performance and Optimization

Due to the web-based nature, we also assessed network and loading performance. The asset bundle size was 28.4 MB across platforms, with over 50 HTTP requests generated. Optimization (e.g., compression, sprite sheets) could reduce this.

Lighthouse scores: desktop 92, mobile 75—affected by

CPU usage and resource limits.

D. Network Performance Evaluation

Performance varies based on network speed and reliability. Compressed textures and binary scene formats help, but poor networks degrade UX.

Caching (e.g., via Service Workers) or preloading using PWA frameworks is recommended to mitigate these issues.

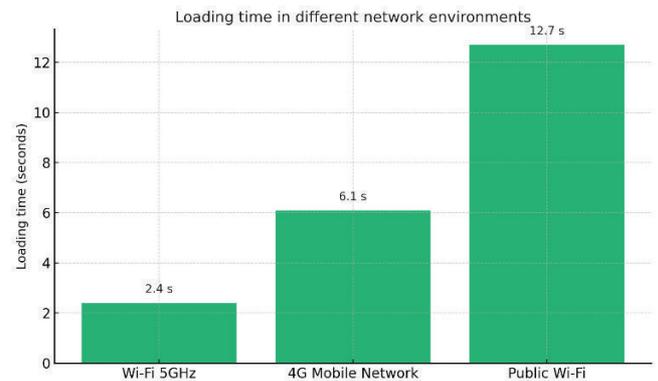


Figure 5. Network performance graph showing load times and latency variations across different network types and conditions.

TABLE 2. NETWORK PERFORMANCE MEASUREMENTS

Network	Load Time (s)	Packet Loss (%)	Latency (ms)
Wi-Fi 5GHz	2.4	0.1	35
4G Mobile	6.1	0.4	88
Public Wi-Fi (Weak)	12.7	2.3	160

IV. PERFORMANCE AND UX CONSIDERATIONS

Testing was conducted on the Pico 4 VR headset.

Key metrics included:

- Average 90 FPS frame rate.
- 11 ms frame render time.
- Under 5 seconds initial load time. Optimizations applied:
- **Runtime batching:** Draw call minimization.
- **Basis Universal:** Efficient runtime texture decompression.
- **Data-Oriented Design:** Cache-optimized data structures.

User feedback confirmed intuitive controls, engaging immersion, and responsiveness.

V. CONCLUSION

Web-based VR has evolved into a viable and increasingly practical platform for immersive content delivery. The case study and measurements conducted across multiple devices, including a standalone VR headset, a desktop PC, and a mid-range smartphone to demonstrate those modern web technologies like WebXR, WebGL 2.0, WebAssembly, and optimized rendering pipelines can deliver responsive, real-time VR experiences directly through the browser.

The testing results revealed that even on limited hardware like mobile phones, acceptable frame rates and input latencies can be achieved. Although performance dropped on mobile devices (averaging 45 FPS), the experience remained functional, which is notable given the reduced GPU capabilities and power constraints.

Latency measurements also supported the platform's viability: input delays were low enough on PC (under 20 ms) and moderate on the Pico 4 (around 42 ms), with tolerable degradation on smartphones. These values, while slightly higher than those on native platforms, still allow for a smooth gameplay experience in casual or educational settings. Importantly, the system remained responsive and consistent across platforms, demonstrating strong cross-device compatibility, since it is one of the major goals of web-based VR.

From a development perspective, the project relied on browser-integrated technologies and open standards such as the WebXR Device API for VR hardware access, Three.js and Wonderland Engine for scene rendering and logic management, and glTF 2.0 with Basis Universal compression for efficient asset streaming. Additional APIs, including the Web Audio API, Gamepad API, and Pointer Lock API were used to enable immersive audio, input tracking, and natural interaction. Performance-critical components were compiled to WebAssembly,

while asynchronous data handling and rendering pipelines utilized Web Workers and OffscreenCanvas to minimize main-thread blocking.

The automated deployment pipeline via GitHub Actions, combined with containerization using Docker, ensured platform independent reproducibility and scalable distribution, further validating the feasibility of using web-native toolchains in professional VR development workflows.

Future research should focus on improving graphical fidelity via WebGPU, integrating machine learning-based personalization or interaction analytics, and expanding toward multiplayer or collaborative VR sessions. These could be powered by WebRTC, which enables real-time peer-to-peer communication with low latency for synchronized VR environments. Complementary technologies such as WebSocket and WebTransport can provide reliable data channels for multiplayer state management, while WebCodecs supports efficient streaming of encoded media between browsers. Together, these protocols can facilitate the creation of shared, persistent virtual spaces accessible directly from the web, without external plugins or native applications.

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Metallic Glass Examination

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Abstract.

One of the most dynamically evolving fields within materials science and modern engineering research is the investigation of amorphous metals, more commonly referred to as metallic glasses. Owing to their unique disordered atomic structure and the resulting exceptional physical properties, metallic glasses present a wide spectrum of application opportunities in high-technology sectors, particularly in electronics, medical technology, and aerospace engineering.

The objective of the present research was to produce metallic glasses through strip casting, using two fundamental metals—aluminum and tin—as well as their alloys. The application of an exceptionally high cooling rate during the casting process enables the molten metal to solidify into a disordered, amorphous ribbon structure. This structural state imparts to metallic glasses their distinctive dual character—simultaneously metallic and glass-like— while also giving rise to material properties that differ significantly from those of the base metals.

Within the scope of this study, several alloy compositions were prepared and subsequently characterized with respect to their electrical resistance and magnetic susceptibility. The experimental data were systematically recorded, tabulated, and analyzed to evaluate the influence of varying alloying ratios on the resulting material properties. The aim of this work extends beyond the mere presentation of measurements; it seeks to elucidate the degree to which amorphous metallic ribbons diverge from their crystalline counterparts, and to explore the potential technological applications that such materials may offer for future engineering solutions.

Beyond the current findings, the long-term ambition of this research is to extend the investigation to additional metals and alloy systems. Such a comparative approach will enable broader insights and foster a more comprehensive understanding of the properties and applicability of metallic glasses. Keywords: metallic glass, examination, alloy

I. INTRODUCTION

It has long been recognized that the crystalline structure formed during the cooling of metals fundamentally determines the mechanical, electrical, and magnetic properties of a given metal or alloy, as well as its resistance to environmental effects. In practice, these properties are regularly modified through so-called heat treatment processes.

Our concept is that by inducing a drastic transformation of the crystalline structure during the solidification of a molten metal or alloy, we are able to significantly influence its properties, and potentially even elicit the emergence of entirely new characteristics.

In our case, the drastic alteration of the crystalline structure means that, during cooling, the oriented crystal growth corresponding to the nucleation centers—and thus the formation of crystallites, i.e., orderly connected crystal aggregates—fails to occur. Instead, a collection of irregularly arranged atomic clusters is formed, which is referred to as an amorphous structure. Since this structural configuration is characteristic of glass, such materials are commonly termed *metallic glasses*.

II. MATERIALS AND METHOD

The technology of metallic glasses is not a recent innovation; its theoretical background has been well described, and practical knowledge is also available. As a foundation for our research, these aspects were presented by László Sajó-Bohus and Csaba Bráda in their 2023 article published in *AIS*. In this work, the authors outlined the theoretical principles of metallic glass technology, described their custom-designed cooling apparatus, and presented the tin metallic glass ribbon they produced, for which they demonstrated the amorphous structure. With this, they confirmed the functionality of the cooling device, as illustrated in Figure 1 [5].

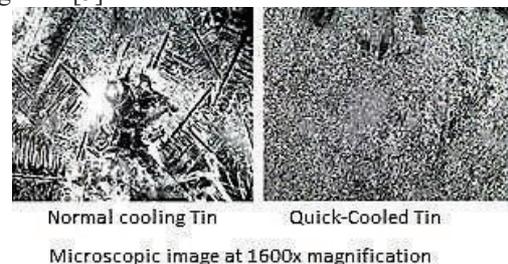


Fig. 1. Microscopic image of the base metal and the metallic glass

III. DESCRIPTION OF THE RESEARCH

As mentioned earlier, the basis of our research was the article presented in the previous chapter. With the authors' permission, we used both the cooling device and the tin metallic glass ribbons produced in their work.

Our research can be divided into two parts:

1. **Production of metallic glass ribbons from materials other than tin**
2. **Investigation and evaluation of the properties of the produced metallic glasses**

Part 1: Production of metallic glass ribbons

In our research, we focused on two base materials: aluminum and tin.

- Tin was available in the form of commercially sold solder, with a composition of 97% Sn and 3% Cu.
- Aluminum was also an industrially available machinable product, the exact composition of which was determined using spectroscopic analysis.

The chemical composition of the aluminum is shown in **Figure 2**.

Cr	0,16
Mn	0,68
Fe	0,31
Al	96,61
Si	1,14
Zn	0,10

Fig. 2. Chemical composition of the aluminum base material

The examinations revealed that the aluminum also contains small amounts of alloying elements (e.g., Si, Fe, Mg), which, according to the literature, may promote the formation of an amorphous structure.

The main considerations during material selection were as follows:

- Both materials are inexpensive and easily accessible.
- Both are easy to machine.
- In the electrochemical potential series, the two materials are relatively far apart.
- According to the literature, the Al/Sn alloy system has been relatively little studied, since the solubility of the two metals is limited and their crystallization tendencies are different. At the same time, this provides an opportunity to observe new and unique structural states during rapid solidification by melt-spinning. [1]

Based on data published in the literature, one of the key factors in the formation of an amorphous structure is that the alloying elements should have significant atomic radius differences and limited crystalline solubility. The Al–Sn system meets both criteria: the atoms of tin and aluminum differ considerably in size and bonding energies, and at room temperature, the two metals are only sparingly soluble in each other. This prevents the formation of a crystal lattice under rapid cooling and instead favors the development of an amorphous structure.

For the experimental investigations, we produced:

- pure tin metallic glass melt-spun ribbons from the solder material described,
- pure aluminum metallic glass melt-spun ribbons, and
- tin/aluminum alloys with different compositions.

The prepared melt-spun ribbons are shown in **Figure 3**.



Fig. 3. Prepared metallic glass melt-spun ribbons

During the production of the alloys, the raw materials were measured out according to their mass ratio. Two main compositions were investigated: the Al₉₀Sn₁₀ alloy (90 wt% aluminum and 10 wt% tin) and its reverse counterpart, the Al₁₀Sn₉₀ alloy. To ensure proper homogeneity, the materials were mechanically crushed. [2]

The experimental fabrication was carried out using a rapid solidification melt-spinning device. The molten alloy was ejected onto the rotating metal wheel of the apparatus, which provided a cooling rate of 10⁵–10⁶ K/s. Under such conditions, crystallization is suppressed, and the atoms solidify in a disordered, amorphous structure.

The mechanical strength properties of the produced alloy ribbons differed significantly. Alloys with higher aluminum content yielded longer and more uniform ribbons, whereas the tin-rich compositions (especially Al₁₀Sn₉₀) proved to be extremely brittle and unsuitable for direct measurements. In these cases, the samples were prepared for testing through pressing. The powdered material was compacted into manageable pellets using a custom-made pressing tool, and these pellets were then subjected to resistance and electrical property measurements.

The raw material prepared for pressing and the final pressed products are shown in **Figure 4**.



Fig. 4. Fragments of the Al–Sn alloy and pellet produced by pressing

Even with a simple manual ball press, it is possible to achieve a pressing force ($F_p \approx 8800$ N for the given press) sufficient to generate a pressure on the tool surface that exceeds the yield strength of both aluminum and tin. In our case, the calculated pressing pressure exceeded 240 MPa, which is significantly higher than the yield strength of aluminum. This method therefore points towards a potential processing route for metallic glasses.

The design of the pressing tool was entirely the result of our own work. We modified the inner chamber and moving parts of the sprayer so that it was capable of compressing the fragmented material and releasing it in the form of uniform test specimens. The pre-weighed, powdered alloy was carefully placed into the tool. During pressing, the material was subjected to high pressure, causing the loose, brittle particles to consolidate into a solid, cohesive pellet.

The pellets produced by pressing were sufficiently stable and mechanically durable to be handled, attached to measuring instruments, and subjected to electrical testing. Thus, this manufacturing approach enabled measurements (such as electrical resistance tests) that could not be performed on the original brittle ribbons.

Overall, it can be stated that pressing technology was not merely an improvised solution, but a key advancement in the context of our research. It allowed us to transform extremely brittle, measurement-inadequate ribbon samples into usable test specimens. The method can also be applied to other alloys that, after rapid solidification, lack sufficient mechanical stability but whose electrical properties are of significant interest.

Part 1: Measurements

Mechanical and physical properties.

Amorphous metals generally exhibit high strength and hardness, but they are prone to brittle fracture. Tin-based alloys are particularly sensitive to cracking, so it was not surprising that the 90% Sn – 10% Al sample proved to be fragile and unmanageable in ribbon form. Even when handled, it crumbled into fragments. By contrast, pure metallic glass ribbons and aluminum-rich alloys showed better mechanical stability and were easier to handle, although the fibrous structure typical of the ribbons still led to easy fracture under tensile load.

We attempted tensile testing on the different samples, but due to the size limitations of the grips on the testing machine, the clamping system requires redesign, which could not be completed within the available timeframe. Preliminary tensile data obtained from trial experiments indicated tensile strengths that compared favorably to tabulated values for the base metals. However, these results are not yet considered exact, and therefore are not reported in detail in this paper.

Electrical properties.

Based on the initial research hypotheses, we expected that the inhomogeneity of the amorphous structure would result in significant deviations in electrical conductivity compared to the known values of pure metals. For aluminum, high conductivity values were anticipated, while for tin, lower values are characteristic.

In alloys – particularly in the $Al_{90}Sn_{10}$ composition – we assumed that the combination of the two metals might result in new, nonlinear behavior, potentially even exhibiting an extreme positive temperature coefficient (PTC). This means that with increasing temperature, the electrical resistance could change significantly, making metallic glasses promising candidates for use in sensors and safety devices. [4] The measurement results are presented in Chapter IV, in Tables 1, 2, and 3.

Corrosion resistance.

One of the outstanding properties of amorphous metals is the absence of a crystal lattice, which significantly slows down corrosion processes. In conventional crystalline alloys, grain boundaries and lattice defects provide favorable initiation sites for oxidation and corrosion. In contrast, the structural disorder of amorphous metals results in more homogeneous chemical distribution and greater resistance against corrosive factors.

In nuclear reactor cooling systems, there is a particularly strong demand for corrosion-resistant materials. In the reactor core environment, the coolant (e.g., water, heavy water, or special fluids such as sodium or other liquid metals) operates under high temperature and pressure. Under these conditions, conventional steel alloys are prone to localized corrosion, stress corrosion cracking, and oxidation, which over time lead to wall thinning and safety risks.

According to the literature, amorphous metals (e.g., Fe-, Zr-, or Al-based metallic glasses) exhibit exceptional corrosion resistance in both aqueous and oxidizing environments. This is because a thin, compact, and adherent oxide film forms quickly on their surface, effectively preventing further corrosion. This property is considered particularly valuable in nuclear energy applications, where the long-term stability of materials is crucial.

From the perspective of our research, the investigation of Al–Sn-based metallic glasses can also be interpreted in this context. Although our primary goal was to study electrical properties, the need arose to evaluate the alloys in terms of corrosion resistance as well. The well-known corrosion-resistant behavior of aluminum, combined with the stabilizing effect of the amorphous structure, provides a promising foundation for such applications.

Further investigations are required to determine the extent to which the Al–Sn system can withstand the extreme conditions imposed by nuclear coolants. Nevertheless, based on the literature and our preliminary findings, it can be stated that the corrosion resistance potential inherent in the amorphous structure represents a highly promising research direction for the development of new materials used in reactor cooling circuits.

As a preliminary study, we carried out a comparative test in which the mass loss of the starting materials—tin, aluminum—and the produced metallic glasses was measured in an identical acidic medium, under 1-hour and 24-hour

exposure cycles. The results are presented in **Table 4 of Chapter IV**.

IV. RESULTS

Due to the structural characteristics of metallic glasses, several distinctive properties are expected in the aluminum, tin, and alloy samples we produced. The absence of a crystal lattice and the disordered distribution of atoms result in physical and chemical properties that differ significantly from the behavior of conventional crystalline metals [3].

This statement is supported by the measurement results obtained from the individual material samples.

- **Table 1** contains the results of the measurements performed on pure aluminum metallic glass meltspun ribbons.
- **Table 2** presents the data for the Al₉₀Sn₁₀ metallic glass ribbons.
- **Table 3** shows the results measured on the Al₁₀Sn₉₀ pressed pellets.

The measured RR (Ω) value represents the actual resistance of the tested specimen, which is influenced by the geometry of the sample. For comparability, the results were recalculated into specific resistivity and conductivity values. On the basis of these specific values, the results can be directly compared to literature data for the base metals.

l (m)	A (mm ²)	R (Ω)	Rfajlagos ($\Omega \cdot \text{mm}^2/\text{m}$)	G ($\text{S} \cdot \text{m}^2/\text{mm}^2$)
0,06 6	0,145	0,104	0,228	4,39
0,06 4	0,142	0,103	0,228	4,39
0,06 2	0,78	0,01	0,126	7,94

Table 1. Actual and specific data of the aluminum samples

Table 2. Actual and specific data of the 90% Aluminum – 10% Tin samples

The Al₉₀Sn₁₀ alloy ribbons exhibited extremely low resistance at room temperature ($\sim 0.03 \Omega$). However, when the sample was exposed to sunlight excitation, the resistance increased drastically to 46.8Ω . This extreme Positive temperature coefficient (PTC) behavior is

l (m)	A (mm ²)	R (Ω)	Rspecific heat ($\Omega \cdot \text{mm}^2/\text{m}$)	G ($\text{S} \cdot \text{m}^2/\text{mm}^2$)
0,06	0,104	0,019	0,126	7,94
0,044	0,14	0,04	0,127	7,87
0,069	0,14	0,012	0,069	14,49
		0,15	0,086	11,62

Table 2. Actual and specific data of the 90% Al and 10% Sn samples

particularly promising for applications in sensors and safety devices.

l (m)	A (mm ²)	R (Ω)	Rspecific heat ($\Omega \cdot \text{mm}^2/\text{m}$)	G ($\text{S} \cdot \text{m}^2/\text{mm}^2$)
0,003	19.62	0,018	117.72	0,00849

Table 3. Actual and specific data of the 10% Al and 90% Sn samples

1. Table 3. Actual and specific data of the 10% Aluminum – 90% Tin sample.
2. The pressed sample of the Al₁₀Sn₉₀ alloy also exhibited interesting behavior when excited by sunlight. The measured resistance value dropped to 0.002Ω , which reduced the specific resistivity to $13.08 \Omega \cdot \text{mm}^2/\text{m}$.
3. Results of corrosion tests.

aqueous solution of phosphoric acid with 0.1 m/m % surfactant mixture			
	initial mass (g)	mass after 1 hour (g)	mass after 24 hours (g)
Al base metal.			
Al ₉₀ Sn ₁₀	3,0	3,0	3,0
Al metallic glass	7,0	7,0	7,0
Sn base metal.	11,0	11,0	11,0
Sn metallic glass			

Table 4. Corrosive property

Significant foaming was observed in aluminum and Al/Sn alloys, indicating material loss. The accuracy of the measuring device is 1 g. The measurement must be repeated with a device of higher accuracy.

V. DISCUSSION AND CONCLUSION

In the course of our experiments, we successfully produced aluminum, tin, and aluminum–tin-based metallic glass ribbons, as well as stabilized pressed specimens. The results clearly demonstrated that the melt-spinning technology is suitable for the formation of amorphous structures. At the same time, the alloy composition had a decisive influence on the mechanical stability and measurability of the samples.

The aluminum ribbons proved to be stable and easy to handle, as expected. Resistance measurements showed a positive temperature coefficient, consistent with metallic conduction models reported in the literature. Tin ribbons were also successfully produced but turned out to be mechanically weaker. Their electrical properties exhibited only moderate variation with temperature, and no measurable magnetic response was observed.

Among the alloys, the Al₉₀Sn₁₀ composition displayed outstanding properties: its resistance was extremely low at room temperature, then increased drastically upon heating. This pronounced PTC effect may be of practical interest in industrial applications, such as temperature sensors and safety devices.

In contrast, the Al₁₀Sn₉₀ alloy was extremely brittle, making it unsuitable for measurement in ribbon form. Pressed pellets provided a partial solution to the problem of measurement, though their mechanical weakness remained a limiting factor.

The investigations highlighted that Al–Sn alloys produced by rapid solidification are promising but also present technological challenges. In line with general properties of metallic glasses mentioned in the literature (high strength, corrosion resistance, soft magnetic behavior), our experiments also confirmed the potential for corrosion resistance and unique electrical responses.

Conclusions:

- Aluminum and tin can successfully be produced in amorphous structure by melt-spinning.

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- The aluminum-rich alloy (Al₉₀Sn₁₀) is particularly promising due to its extreme PTC behavior.
- The tin-rich alloy (Al₁₀Sn₉₀) requires pressing because of its mechanical instability, which provided a partial solution to its measurability.

In the future, it will be worthwhile to investigate possibilities for further increasing the mechanical strength, to test new alloying ratios, and to carry out detailed corrosion tests. In addition, alternative heat treatment and pressing technologies may also contribute to expanding the industrial applicability of the Al–Sn system.

- Based on our investigations, Al–Sn metallic glasses may in the future find applications in sensors, safety systems, and potentially in the energy industry, where corrosion resistance is required, such as in the cooling circuits of nuclear reactors.
- Future research should focus on improving mechanical strength, exploring new alloy compositions, and conducting detailed corrosion assessments. Furthermore, different heat treatment and pressing technologies could enhance the potential of the Al–Sn system for industrial use.

Comparative Analysis of a Traditional and an Industry 4.0-Based Manufacturing Cell through the Example of a Cylindrical Gear

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Abstract — *This paper compares a traditional production line and an Industry 4.0-oriented manufacturing cell through the example of a cylindrical gear produced in three aluminium variants. The study evaluates productivity, flexibility, quality, and cost efficiency, and examines the impact of Industry 4.0 elements such as sensors, data analytics, and automated control. Results show that traditional systems remain effective in small- and medium-scale production, while Industry 4.0 solutions excel in high-volume and precision-demanding environments. The findings highlight the potential of hybrid strategies that combine conventional robustness with digital adaptability.*

Keywords: *Industry 4.0, manufacturing cell, gear, comparison, comparative analysis.*

I. INTRODUCTION

The primary aim of this publication is to provide a comparative analysis of traditional manufacturing systems and those that comply with Industry 4.0 standards. The study focuses on comparing the operating principles, tools, and organizational logic of two fundamentally different approaches to manufacturing. The subsequent analysis also considers various application contexts, advantages, and challenges.

It is important to emphasize that this paper does not aim to rank the two approaches or to declare one superior. Rather, the objective is to identify the manufacturing environments and conditions where either system can offer greater benefits.

The purpose of this work is to highlight, from a practical perspective, the factors that influence the advantages of a given system, as well as the compromises and challenges that must be addressed when selecting a manufacturing strategy. In this way, the paper seeks to provide support for students and educators involved in the development, design, or optimization of manufacturing systems.

In this study, the term “traditional manufacturing system” refers to production structures that rely little or not at all on digital technologies. In such systems, the level of automation is generally lower, human labour

plays a more dominant role, and decision-making is conducted by people based on experience. Examples include classical production lines, manual or semiautomated workflows, and manufacturing cells operating with quite simple control systems.

By contrast, Industry 4.0-based systems represent integrated, digitized, and often selforganizing production environments. In such manufacturing cells or lines, the various devices communicate with each other, collect and process data about themselves and their surroundings, and can make decisions based on predefined algorithms. The aim of these systems is to minimize the need for human intervention, thereby reducing errors and optimizing manufacturing efficiency.

As part of this paper, specific examples designed by the author are presented to demonstrate the characteristics of these systems and ways in which they can be optimized. Special attention is given to the forms of human–machine collaboration and the role of data-driven decision-making.

II. INDUSTRY 4.0 CONCEPT AND FOUNDATIONS

Industry 4.0 involves linking physical and digital systems so that production lines, machines, sensors, and IT systems become intelligent, networked units. These systems not only collect data but are also capable of real-time analysis and automatic optimization of production processes. Industry 4.0 fundamentally relies on technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, cloud systems, robotics, cyber-physical systems (CPS), and big data analytics.

In an Industry 4.0-compatible manufacturing system, machines can communicate with each other, make decisions, and adapt to changing conditions.

The close integration between systems makes production more flexible, faster, and cost-effective, depending on the characteristics of the manufactured product. This is particularly important in today’s

rapidly changing market environment, where personalized, small-batch production is increasingly common.

The aim of Industry 4.0 is not merely to automate production but to create an intelligent, adaptive, and predictive system capable of independently responding to unexpected events, errors, or order changes. This significantly reduces the need for human intervention while increasing manufacturing efficiency and quality.

It is important to note, however, that Industry 4.0 is not just a technological innovation but also a shift in mindset. It represents a complex ecosystem in which not only production but also logistics, maintenance, quality assurance, and product design are conducted in a digital, data-driven manner. This requires not only innovative technologies but also new competencies, training, and corporate culture.

The introduction of Industry 4.0 is therefore not a universal recipe but a process that varies by company. Its success depends heavily on existing infrastructure, human resources, financial capacity, and the strategic commitment of management.

III. MACHINE AND HUMAN INTERACTION IN MANUFACTURING

The goal of industrial automation is to make production processes faster, more predictable, and cost-effective. Automation replaces human tasks that are typically repetitive, well-defined, and do not require creative or intuitive decision-making.

What makes a task automatable?

Several factors determine whether a task can be automated. A basic requirement is that the task must be precisely defined: it should consist of clear steps with measurable inputs and expected outputs. For example, screwing a bolt, positioning a component, or performing a simple quality check can be relatively easy to automate. It is also important that the environment is stable and well-controlled—for example, closed manufacturing cells have fewer external disturbances, making it easier to design an automated system.

Where do automated lines excel?

Automated production lines perform exceptionally well in areas where the goal is to produce large quantities of standardized products. Their advantages include high speed, excellent repeatability, favorable error rates, and reduced physical strain on workers. Modern systems can already perform self-diagnostics, predictive maintenance, and dynamic adjustment of production parameters.

What cannot be replaced by machines?

Machines are excellent for rule-based tasks but still face challenges in replacing complex human skills such as complex decision-making, flexibility, emotional intelligence, or creativity. Problemsolving, handling unexpected disruptions, or rapidly adapting to new processes are areas where humans still outperform machines. Furthermore, machines cannot weigh moral, ethical, or social considerations, which may be essential in certain situations.

What is the human role in an automated environment?

In a modern, Industry 4.0-compatible manufacturing environment, the human role is transformed but not eliminated. Instead of physical labor, supervision, control, data interpretation, decision-making, and development take center stage. Tasks include system maintenance, optimization, and identifying the causes of production anomalies. Operators must acquire additional skills and training to transition from traditional machine operation to these new responsibilities. A general shift in mindset is also required to embrace the interpretation and use of production-related data.

IV. WORKPIECE AND MANUFACTURING

The comparative analysis of this thesis is realized through examining a traditional and an Industry 4.0-compliant manufacturing cell. The chosen workpiece is a gear, a common machine element used in many assemblies. Its manufacturing operations include turning, gear cutting (e.g., hobbing or milling), drilling, and final quality control.

The study covers the production of six different types of gears differing in the outer diameter (40mm, 60mm, 80mm) and the number of teeth (20,30,40).

The ability to handle these three types ensures that the flexibility, changeover capability, and production strategy of the production lines can be compared. This makes it possible to analyze the steps required to manufacture each type in the two different systems and to examine differences in efficiency, manageability, data handling, and labor requirements.

The aim of the manufacturing system is not merely to produce parts but to highlight when a traditional approach is more advantageous and when it is worth exploiting the possibilities of Industry 4.0.

The study does not aim to identify a “better” or “worse” system but to determine which approach offers more benefits in different manufacturing situations.

V. TRADITIONAL MANUFACTURING PROCESS

The traditional manufacturing cell is built on linear, sequential operations performed on

separate machines or workstations. The operator moves the workpiece from one machine to another, starting each operation with manual setup and supervision.

During the process, there is little or no data communication between machines. Production status is typically tracked in a simplified manner using spreadsheets or verbal reports. After production, the number of good parts, scrap, and rework quantities are recorded in a digital system.

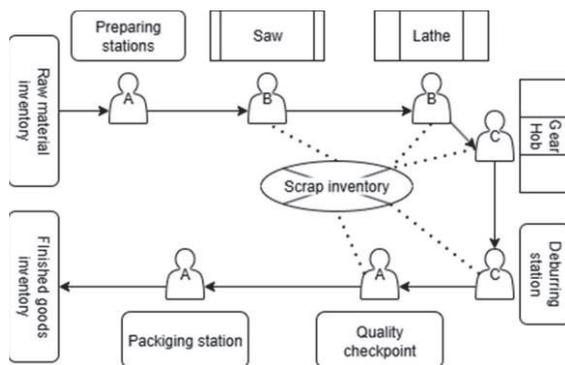
Process main steps:

1. Raw material preparation: bar stock cutting with manual or semi-automatic saw.
2. Turning of outer diameter and creation of internal bore.
3. Gear cutting using a gear milling cutter.
4. Manual removal of burrs.
5. Quality inspection using calipers, micrometers, or gauges.
6. Manual movement of the part between processes.

Several layout alternatives illustrate the flexibility of traditional manufacturing. The arrangement has a direct impact on efficiency, cycle time, and work organization.

VI. TRADITIONAL MANUFACTURING BLOCK DIAGRAM

The block diagram of the traditional manufacturing cell follows a simple, linear layout in which the individual workstations are arranged sequentially.



6.1 Figure: Traditional Manufacturing

The primary goals of this design are to maintain the correct order of operations, ensure easy movement for operators, and keep the production process transparent. Material flows from left to right.

By design, 2–3 operators are present in the cell, and their assignments can be freely adjusted according to their experience.

The operators’ tasks in this structure include:

- Workpiece preparation.
- Manual control and supervision of machining equipment.
- Quality inspection.
- Maintenance activities.
- Manual documentation of production data.
- Communication with other operators.

VII. INDUSTRY 4.0

MANUFACTURING PROCESS

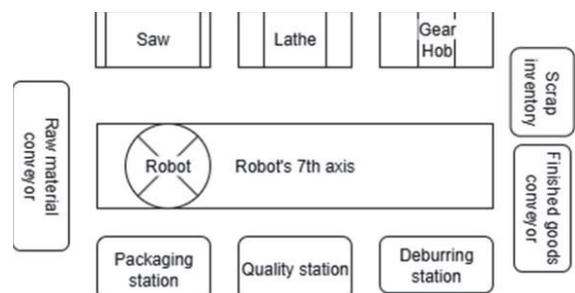
The design of the Industry 4.0-compliant manufacturing cell is based on the latest technologies to achieve efficient, flexible, and fully automated production.

Key features:

- Digital production order reception (from MES or ERP)
- Workpiece identification and preparation using RFID.
- Automated gripping and feeding (robot arm with 7th axis)
- CNC machining with real-time sensor data
- Camera-based automatic quality control
- Data collection and cloud-based feedback (IoT)
- Automated storage and reporting to the central system

The main stages include order processing, sawing, turning, milling, deburring, quality control, and packaging, with robotic transport of raw materials, workpieces, and finished products.

VIII. INDUSTRY 4.0 BLOCK DIAGRAM



7.1 Figure: Industry 4.0 block diagram

The system’s key advantage is modularity and intelligent control: the cell can adapt to changing production needs without lengthy downtime or manual intervention. Continuous data collection enables predictive maintenance and production optimization.

- The main elements of the cell include:

- Raw material conveyor
- Automatic saw - Lathe
- Gear milling machine.
- Deburring station
- Camera-based quality inspection station
- Packaging station - Finished
- product conveyor. - Scrap collector
- Industrial robot arm and 7th axis

The operator's role is almost completely transformed compared to traditional manufacturing, focusing on system monitoring, data management, program handling, anomaly intervention, and maintenance.

IX. INDUSTRY 4.0 COMMUNICATION ARCHITECTURE

The Industry 4.0 manufacturing cell features real-time communication between machines, systems, and humans. Every component must communicate with each other and a central system to enable accurate process tracking.

Communication includes:

- Database interactions for fault logging, tolerance monitoring, and product tracking via RFID.
- Robot coordination with conveyors, machining stations, quality control, packaging, and scrap collection.
- PLC-based real-time data flow to ensure smooth operation.

The operator now performs data verification, troubleshooting, and system supervision rather than solely physical control.

Communication Parties:

Database:

Failures are recorded in the database. If a disturbance occurs at one station, it must be communicated to the others in order to suspend production. If the system produces values beyond tolerance, it must send feedback to the operator.

The RFID of every manufactured product and its associated data must be logged. This includes whether the final product is suitable for the customer, requires rework, or is scrap.

Raw Material Conveyor:

Database – Based on extracted data, it initiates the transport of raw materials and stops the process when the material reaches the end-position sensor.

Robot – The robot must be aware that the raw material has reached the predefined position.

Processing Stations:

Database – The database must contain at least an approximate status of the tool. It must log when and what type of material entered and exited the workstation so that its status can be tracked and modified if necessary.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Quality Control Station:

Database – The station must transmit cameracaptured images to the database. In case of discrepancies, this plays a particularly important role.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Packaging Station:

Database – The station must provide information to the database about the accurately packaged good product.

Robot – The robot must know the current work stage of the station and whether it is accessible and loadable.

Scrap Collector:

Robot – Database communication. Based on how many times the robot moved to the scrap collector, the amount of scrap produced can be determined. Therefore, the scrap collector does not need to be equipped with additional sensors.

Robot's 7th Axis:

Robot – Continuous communication must be maintained between the robot and the axis to ensure that work processes can be carried out.

Most of the required data flow can be easily implemented using PLCs. It is essential that communication is real-time. The operator's role has significantly changed compared to traditional control: they not only perform physical interventions but also carry out data verification, troubleshooting, and system monitoring.

This network enables data-driven decisionmaking, instant fault detection, and real-time optimization of the production process—capabilities that were difficult or impossible to achieve with traditional production lines.

X. COMPARISON OF PROCESSES

The aim of this chapter is to provide an extended comparative evaluation between the traditional manufacturing process model and Industry 4.0-based systems.

The essence of the traditional model lies in its linear and segmented progression, where decisionmaking and quality control are primarily in the hands of human operators. In this setup, intermediate inspections occur at various stages of the workflow—for example, after cutting, turning, or gear machining, product parameters are manually checked or assessed at inspection points, and decisions are made regarding rework or scrapping. The advantage of this experience-based model is that skilled operators can perform quick, situationspecific interventions in particularly complex scenarios. However, this approach carries a higher risk of errors, as manual inspections are often delayed, may result in inconsistent quality levels, and coordination between workflow stages can become cumbersome due to the lack of continuous feedback.

In contrast, the Industry 4.0-based structure is equipped with digital and automated solutions, enabling the manufacturing process to operate not only in predefined steps but also dynamically, based on real-time data flow and processing. The application of cutting-edge technologies allows deviations in raw material and inventory management, as well as in machine operations, to be identified early in the production phase. This enables predictive maintenance and intelligent decisionmaking. Real-time quality control and data continuously monitored by algorithms significantly reduce production errors and correction times, although the system requires high-level technological investment and a different type of operator expertise.

From the outlined perspectives, the comparison essentially reflects a clash of two philosophies: while the traditional model relies on human factors and experience-based, segmented feedback, the Industry 4.0 approach aims to eliminate delays and error potential stemming from human nature through continuous data flow, predictive analytics, and automated interventions. This can lead to increased productivity, improved quality assurance, reduced cycle times, and significant long-term cost savings. However, the traditional system may prove more flexible in cases where environmental or productspecific characteristics prevent standard automation algorithms from making optimal decisions, making human intervention indispensable.

Furthermore, the Industry 4.0 model enables integrated process management, where every phase of the production cycle—from raw material intake to final product packaging—operates within a centralized,

interconnected system. An example of such a process system was detailed in previous chapters of this thesis. This system-level integration not only improves production speed and quality but also supports early forecasting of maintenance and optimization decisions, which can lead to a reduction in the proportion of defective workpieces. In contrast, the traditional model is decentralized, with less transparent data flow between subsystems, making rapid error detection and correction more difficult.

The comparative evaluation highlights that Industry 4.0 systems, driven by digital integration, are more competitive, flexible, and capable of significantly reducing unforeseen disruptions in the long run. However, the high investment costs and comprehensive challenges associated with these systems must not be overlooked. The experiencebased flexibility and adaptive human decisionmaking of the traditional model remain valuable in situations where unique production requirements demand personal intervention. In future industrial systems, it is likely that both approaches will be applied in parallel: automated, real-time data-driven decision support will be complemented by the role of experienced operators, who will ensure continuous product compliance by reviewing system-generated alerts and recommendations.

XI. SUMMARY

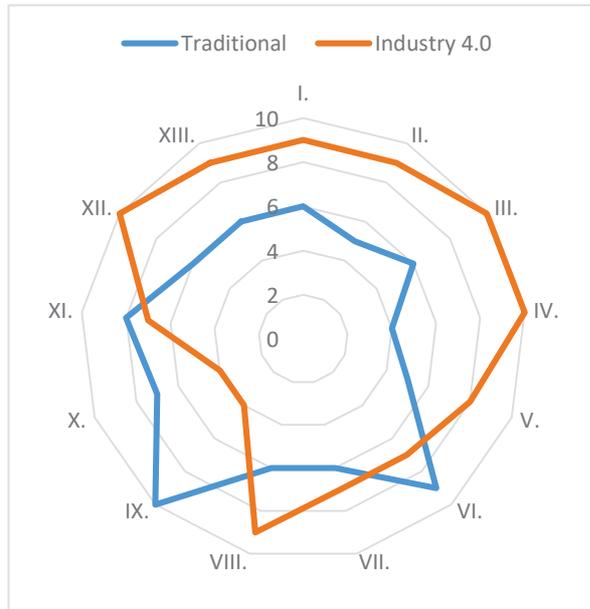
The aim of this research was to compare the operation, structure, advantages, and limitations of traditional and Industry 4.0-oriented manufacturing cells through the example of a specific workpiece. The investigation revealed that both manufacturing approaches possess strengths that may make one more advantageous than the other depending on the context.

Traditional systems, due to their simplicity and proven reliability, remain suitable for lowcomplexity, small- or medium-batch production. In contrast, Industry 4.0 technologies—including automation, sensor networks, robotics, and datadriven decision-making—are particularly beneficial in high-volume production environments with stringent quality requirements or frequent changeovers.

A key finding is that Industry 4.0 is not solely about technology—it also represents a shift in mindset. Human labour does not disappear but transforms: physical tasks give way to supervisory, system-level, and decision-making roles. This demands new skills and ways of thinking from industrial workers.

The future of manufacturing lies in integrating both approaches—where the stability of traditional systems complements the flexibility of Industry 4.0. Continuous development and research are essential for industrial stakeholders to fully leverage the opportunities offered by digitalization.

To illustrate the differences between the traditional and Industry 4.0 based manufacturing cells this evaluation table was created based on my own observations and experiences. The table compares the two systems across several operational and organizational aspects, assigning numerical values (1-10) to represent their relative performance and capabilities.



XI.I figure: difference evaluation diagram

I.	Process structure	VIII.	Logistics and inventory support
II.	Decision-making method	IX.	Cybersecurity
III.	Quality control	X.	Investment requirements
IV.	Data collecting and processing	XI.	Operator's role
V.	Maintenance	XII.	Performance monitoring
VI.	Flexibility and intervention	XIII.	Innovation potential
VII.	Scrap and rework handling		

XI.II figure: table for evaluation diagram content

Based on the research findings, there is potential to develop software capable of evaluating whether a given process can be technically and economically automated based on predefined parameters. Such a system could consider production volumes, product variability, investment costs for automation, the condition of existing machinery, and human resource requirements.

The examples examined in the thesis (e.g., production of cylindrical aluminum gears) demonstrate that even seemingly simple products may require diverse technological and organizational approaches. The choice is often not straightforward and involves trade-offs: for instance, an automated system may be faster and more precise, but its investment cost is high

and only pays off at larger batch sizes. Such software could provide answers to these questions through objective, calculation-based decision support.

In the long term, the concept could be enhanced with an AI-based learning module that refines predictions using historical production data. This would allow the system not only to evaluate individual data points but also to improve its recommendations through experience and machine learning.

In conclusion, future manufacturing decisions should not rely solely on technological intuition or experience but increasingly on data-driven, modelbased evaluation systems. Such a decision-support tool could also contribute to the competitiveness of domestic small and medium-sized enterprises by helping them identify and optimize manufacturing development opportunities in a structured way.

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All diagrams included in this thesis were created manually using the draw.io software. All tables presented in the thesis were manually compiled using Microsoft Excel. The preparation of this thesis was supported by Artificial Intelligence tools. Specifically, OpenAI ChatGPT and Microsoft Copilot were used to assist with text editing suggestions, structural ideas, and content formatting.

Metaverse in the Aviation Industry – A Challenge to be Addressed

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Abstract—The Metaverse represents a rapidly developing digital platform that opens up new possibilities for innovation across various industries. The aviation industry, as one of the most technologically demanding and regulated sectors, is beginning to take an active interest in the potential of using metaverse in areas such as personnel training and certification, optimizing flight operations, aircraft maintenance, and improving customer experience. This paper aims to identify key areas where the metaverse can bring added value to the aviation sector, provides an overview of the use of the metaverse in the aviation industry, discusses the technological prerequisites for its implementation, and the challenges associated with integrating these new solutions into the existing infrastructure and regulatory framework.

Keywords—aviation, metaverse, digitalization, virtual reality, augmented reality

I. INTRODUCTION

The aviation industry is currently facing rapid technological advances that are fundamentally changing the way airlines, airports, and the entire air transport ecosystem operate. These changes are reflected not only in increased operational efficiency and safety, but also in an enhanced passenger experience and more efficient internal processes. The dynamic development of digital technologies and the emergence of the Metaverse concept are bringing new opportunities for optimizing and digitizing processes in aviation. Virtual and augmented environments enable airlines and airport operators to link real-world operations with digital simulations and interactive platforms. This allows companies in the aviation industry to increase the efficiency of their services, improve the customer experience, and optimize internal processes such as employee training, operations planning, aircraft maintenance, and customer communication.

Metaverse technologies, combined with artificial intelligence, virtual reality (VR), and augmented reality (AR), enable the creation of digital twins that simulate the real infrastructure of airports, aircraft, or logistics operations. These solutions contribute to reducing costs, streamline work processes, and increase the safety and reliability of operations, according to the Capgemini Research Institute in 2022 [1]. The Metaverse in aviation is thus ceasing to be just a marketing concept and becoming a practical tool for improving and streamlining business processes and innovation. This article provides an overview of the most important companies in the aviation industry that are making the best and most effective use of these technologies and identifies the most significant areas for process efficiency through the application of Metaverse technologies based on the materials obtained and personal interviews.

II. OVERVIEW OF THE USE OF METAVERSE IN THE AVIATION INDUSTRY

Virtual Reality (VR) and Augmented Reality (AR) technologies began to gain popularity in the 1990s, primarily in the gaming and entertainment industries. One of the first companies to explore their potential in the aviation industry was Boeing. In the 1990s, Boeing began experimenting with AR to improve the manufacturing process, with technicians using AR glasses to assemble electrical cables in aircraft. A significant pioneer in the field of VR simulation and training was the Canadian company CAE Inc., founded in 1947, which specialises in the development of flight simulators. In the 2000s, CAE began integrating VR into its simulators, creating a more realistic and interactive training environment for pilots [2].

Airlines have begun to recognize the potential of Metaverse technologies to improve customer service and training. One of the first was Lufthansa's Lufthansa Aviation Training (LAT) division, which implemented VR simulators for pilot training. This initiative was motivated by the need to reduce the costs of traditional simulators and provide more flexible training options [3].

As reported by the International Journal of Aviation, Aeronautics, and Aerospace [4], key players in the early stages of the concept included Boeing, which is one of the most important companies that has contributed to the integration of metaverse technologies in the aviation industry. Their implementation of AR to streamline manufacturing and maintenance processes has brought significant improvements in accuracy and efficiency. Boeing has also announced plans to develop a "digital factory" in the metaverse, where engineers from around the world will design aircraft in a single shared 3D environment using XR tools and AI. This supports global collaboration without the need for physical presence [5].

Airbus has also played a key role in adopting metaverse technologies. Their "Smart Glasses" application uses AR to provide digital manuals and visualizations to technicians, reducing errors and increasing maintenance efficiency [6].

Lufthansa Aviation Training (LAT) has been a pioneer in integrating VR into pilot training. Their use of VR simulators allows pilots to train in a realistic environment without the need for a physical simulator, significantly reducing the costs and logistical challenges associated with traditional training methods (Table I) [4].

TABLE I. VR SIMULATION COMPONENTS FOR CREW TRAINING

Component	Usage
VR Headset	It provides an immersive visual and audio environment for realistic simulation.
Simulated pressure/smoke	Some advanced VR simulators use physical effects (e.g., smoke walls).
Scoring System	Training sessions are evaluated based on speed, accuracy, and consistency of responses.
Replay/Analysis	Training sessions can be replayed and analyzed to review decisions and procedures.

The Federal Aviation Administration (FAA) uses VR to train air traffic controllers, improving their reaction times and decision-making in challenging situations. This initiative contributes to increased flight safety and improved controller performance [7].

In aviation, blockchain can be used to secure data on an aircraft's technical history or maintenance records. Using NFTs (Non-Fungible Tokens), it is possible to uniquely identify aircraft parts (components) or verify a digital certificate of ownership. For example, GE Aviation is testing blockchain to track the history of aircraft components for maintenance purposes [8].

The development, implementation, and streamlining of Metaverse technologies in the aviation industry are supported by numerous expert studies and research. A significant study published in the Journal of Air Transport Management [6] examines the impact of VR simulators on pilot training and identifies key benefits such as improved emergency preparedness and reduced training costs. The idea of using the Metaverse in the aviation industry arose in response to the need to increase efficiency, safety, and service quality. Key players such as Boeing, Airbus, Lufthansa Aviation Training, and the FAA have played an important role in adopting and implementing these technologies to streamline processes through the Metaverse in aviation [9].

According to a study by Accenture, the metaverse in aviation also makes it possible to create digital twins of aircraft and airports, simulate flight situations, and build virtual workplaces for employees, leading to increased efficiency and safety [10]. Rolls-Royce uses digital twins of its engines, which track thousands of data points during flight and provide information on component wear, enabling predictive maintenance.



Fig. 1. Roll Royce UltraFan Jet Engine (Source: ROLLS-ROYCE. Digital Twin [online]. [cit. 2025-03-02]. Available at: <https://www.rolls-royce.com/innovation/digital/digital-twin.aspx>)

The picture above (Fig.1) shows the UltraFan engine, which is equipped with digital twin technology. Each fan blade has its own digital twin that stores data from real-world tests. This technology allows engineers to predict engine performance during operation and optimize maintenance [11].

TABLE II. AIRLINES AND THEIR USE OF METAVERSE TECHNOLOGIES IN AVIATION

Company	Technology	Metaverse Use	Year of Implementation
Emirates Group	Emirates Metaverse, NFT collection	Virtual check-in, board tour, NFT products	2022
Lufthansa Group	Innovation Runway, VR Training	VR staff training, AR for ground services	2022 – 2023
Qatar Airways	QVerse – Metahuman Cabin Crew	3D aircraft tour with an avatar in VR	2022
Singapore Airlines	Digital Twin Technology	Airport and maintenance simulations in digital twins	2023
Accenture	Metaverse Strategy for Travel	Consulting services, virtual customer experiences	since 2022
Microsoft	Microsoft Mesh Platform	Virtual workspaces, VR training	since 2021

Table II provide an overview of the Metaverse usage in aviation and the year of their implementation. Expert studies and research confirm the benefits of the Metaverse for the aviation industry and provide valuable insights for further development and innovation. In other words, based on the above information, we can say that Metaverse components are positively transforming the aviation industry, from training and maintenance to customer service and engineering. Their implementation leads to greater efficiency, safety and innovation in aircraft operation and development. Despite challenges such as cost, technology standardisation and data security, the Metaverse in aviation is opening the door to a new era of digital aviation.

III. KEY AREAS FOR PROCESS EFFICIENCY IMPROVEMENTS USING METAVERSE IN THE AVIATION INDUSTRY

This section focuses on an overview of key areas where Metaverse technology is most commonly used to streamline processes in the aerospace industry. From training and simulations to maintenance and technical support to design and customer service, Metaverse delivers innovative solutions that transform established practices and contribute to greater efficiency and safety across the industry.

A. Crew and Employee Training

Lufthansa Aviation Training (LAT) has developed a VR program for training cabin crew, which was the first of its kind to be approved by the German Aviation Authority. Since its introduction in 2019, approximately 20,000 flight attendants have completed the program. VR training enables realistic simulations that increase efficiency and reduce the costs associated with traditional training methods. Lufthansa Aviation Training (LAT) has achieved increased efficiency and cost savings in cabin crew training by implementing virtual reality (VR) based on several key factors:

- Reduced need for physical simulators
- Increased training capacity
- Increased training efficiency
- Reduced training costs [12]

B. Technical maintenance and predictive diagnostics

Lufthansa Technik has achieved significant improvements in technical maintenance and predictive diagnostics by implementing augmented reality (AR) and virtual reality (VR) technologies. These technologies have enabled more efficient training of mechanics, more accurate diagnostics, and faster repairs, leading to increased efficiency and reduced costs. Since 2021, Lufthansa Technik has been testing various XR technologies for maintenance, training, and marketing applications. The use of AR allows mechanics to obtain an "X-ray" view of engine components, improving the accuracy and speed of repairs. VR is used to train mechanics in areas such as engine component identification and endoscopic inspections, e.g.:

- XR training in MRO (maintenance, repair, overhaul),
- XR (augmented reality, virtual reality, mixed reality) demonstration applications designed for training mechanics in the field of MRO in cooperation with Lufthansa, Technical Training: AR training in cockpit procedures (Cockpit Procedure Training), VR training in the localization and identification of engine components and VR training in engine endoscopy — visualization of all engine surfaces in a 360-degree view.

C. Customer support and onboarding

In this area of process improvement, Emirates is again a good example, having developed a virtual reality (VR) platform called MIRA (Mixed Reality Training) for training cabin crew. This platform allows crew members to interact with a virtual environment and improve their skills in realistic scenarios (Fig. 2). MIRA offers self-guided, multi-user training modules that allow staff to virtually practice operations such as door handling and firefighting in realistic cabin environments.

Key features of the MIRA platform:

- Realistic simulations: MIRA provides a highly realistic audio-visual environment that allows the crew to practice various scenarios, such as door handling, firefighting, and cabin evacuation.
- Multi-user training modules: The platform supports simultaneous training of multiple crew members who interact via avatars in a shared virtual space.

- Self-paced training: Crew members can complete training at their own pace, which increases flexibility and contributes to more effective learning. Emirates plans to train approximately 23,000 cabin crew members using the MIRA platform, including training for the Airbus A380, Boeing 777, and Airbus A350 aircraft. The implementation of VR training enables faster and more efficient crew training, leading to better preparedness for emergency situations and reducing the need for physical simulators. MIRA enables crew training without the need for physical presence at a training center, reducing logistics costs and enabling remote training.



Fig. 2. Simulation of Emirates crew training using avatars in virtual space (Source: EMIRATES. Emirates cabin crew to step into the virtual world for safety training [online]. [cit. 2025-01-16]. Available at: <https://www.emirates.com/media-centre/emirates-cabin-crew-to-step-into-the-virtual-world-for-safety-training/>)

D. Logistics and supply chain management

Boeing has implemented digital twin technology to optimize its manufacturing processes and supply chains. This technology enables the creation of virtual models of aircraft and production lines, leading to more efficient planning, reduced costs, and improved quality.

One example is the use of digital twins in the T-7A Red Hawk program, where Boeing achieved an 80% reduction in assembly time through model engineering and 3D design. Similarly, in the production of the MQ-25 aircraft, engineers use digital models to verify compliance with technical specifications, which increases the accuracy and quality of production [13].

In the area of supply chains, Boeing uses digital twins to simulate and optimize logistics processes, enabling better prediction of problems and more efficient inventory management. This technology provides a comprehensive view of the entire chain, increasing transparency and enabling faster decision-making [14].

E. Flight simulation and cabin design

Singapore Airlines (SIA) has implemented virtual reality (VR) technology as part of its KrisLab digital innovation lab to improve aircraft cabin design and customer experience. This initiative allows designers to test and modify cabin concepts more efficiently, leading to an optimized design process and improved passenger comfort. Opened in 2019, KrisLab serves as a collaborative space for SIA employees to develop innovative ideas and collaborate with external partners. One of the main projects is the use of VR technology, which allows designers to virtually enter the aircraft interior and interactively change design elements in real time. This approach simplifies the design process and allows potential problems to be identified and resolved more quickly.

The benefits of implementing Metaverse virtual technologies are mainly reflected in:

- *Increased training efficiency:* Mechanics can train in a realistic virtual environment, which increases their preparedness for real-life situations.
- *Reduced training costs:* VR training reduces the need for physical models and equipment, thereby reducing the costs associated with traditional training methods.
- *Improved repair accuracy:* AR technologies provide mechanics with accurate visual instructions, reducing the risk of errors during repairs.
- *Faster repairs:* The use of AR and VR technologies reduces the time needed for diagnosis and repair, resulting in faster return of aircraft to service.
- *Accelerated design process:* The implementation of VR has enabled designers to test and modify designs more quickly, resulting in a reduction in the time needed to develop new designs.
- *Improved customer experience:* The ability to simulate and evaluate from the passengers' perspective before physical implementation allows for the optimization of interior comfort and functionality, contributing to higher customer satisfaction.
- *More effective collaboration:* Support for collaboration between employees and external partners, including startups and research institutions, leading to faster development and implementation of innovations.

IV. QUANTIFYING THE BENEFITS OF METAVERSE IN THE AVIATION INDUSTRY

The introduction of Metaverse technologies into the aviation industry brings significant changes in the way processes are managed, quality is improved, and costs are optimized. The following section focuses on a quantitative assessment of the impact of these technologies in key areas of airline operations. The data obtained presents the specific benefits that have been achieved through the implementation of virtual and augmented reality, digital twins, and other Metaverse tools.

By comparing indicators such as cost savings, time reduction, and quality improvement, it is possible to better understand the processes in which these innovations have the greatest effect. Visualizing these results in the form of a graph provides a clear overview of how the Metaverse can contribute to streamlining aviation operations and achieving greater customer satisfaction and more efficient operations based on the information obtained (Fig. 3).

The highest efficiency in terms of cost reduction (40%) and time reduction (55%) was achieved through crew and employee training, with the quality of training also increasing to 90%. Technical maintenance and diagnostics saw 25% cost savings and 30% time efficiency, with work quality increasing to 85%. In the area of customer support and onboarding, costs were reduced by 15%, processes were accelerated by 25%, and the customer experience was improved by 80%. Logistics and supply chain management delivered 20% cost savings and the same time efficiency, while process quality increased by

75%. Flight simulation and planning enabled a 30% reduction in costs, a 35% reduction in time, and an 85% increase in design quality. These results demonstrate the significant potential of the Metaverse in optimizing operational, training, and customer processes in the aviation industry.

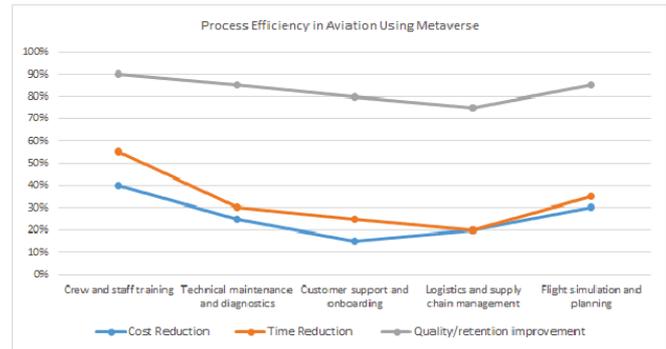


Fig. 3. Process Efficiency in Aviation Using Metaverse (Source: Grami, L. *Metaverse v leteckom priemysle*. 2025. Košice)

The graph clearly demonstrates that Metaverse has the greatest effect in terms of improving quality and sustainability in crew training (90%) and flight planning and simulation (85%). The most significant time savings (55%) and cost savings (40%) were achieved in staff training, confirming that education is the most quickly monetizable part of Metaverse implementation in aviation. Areas such as technical maintenance and logistics management achieved very solid results, particularly in reducing errors and speeding up work, which has a long-term positive impact on the safety and reliability of airline operations. These results support the recommendation that airlines should start with training, maintenance, and customer experience for successful Metaverse implementation.

V. CHALLENGES AND LIMITATIONS IN THE USE OF THE METAVERSE IN THE AVIATION INDUSTRY

The implementation of Metaverse technologies in the aviation industry represents a revolutionary step in the digitization of processes, training, maintenance, flight planning, and customer support. As practical examples from companies such as Lufthansa Group, Emirates Airlines, Boeing, and Singapore Airlines show, the use of virtual and augmented reality, digital twins, and artificial intelligence brings demonstrable benefits in the form of reduced costs, shorter process times, and improved service quality. Despite these benefits, airlines face a number of specific challenges and limitations when applying Metaverse technologies, which can complicate, slow down, or increase the cost of the implementation process.

One of the most significant obstacles to the deployment of Metaverse technologies in the aviation sector is the high initial investment costs. Given the complexity of these solutions – from the development of software platforms, through the purchase of specialised hardware, to staff training – this is an extremely capital-intensive process. Deploying Metaverse requires not only investment in computing technology and infrastructure (e.g. 5G, data servers, VR/AR devices), but also a long-term digital transformation strategy. For smaller airlines and regional airports, the introduction of Metaverse technologies poses a significant challenge, particularly from a financial and technological perspective. Implementing Metaverse solutions on a smaller scale may not

bring the same return on investment as it does for large companies. Another negative factor may be the technological unpreparedness of infrastructure, which requires additional modernization costs. Another barrier is the lack of qualified personnel to manage these systems and the risk that the investment will not bring the expected results due to a limited customer base [15].

The deployment of Metaverse technologies in aviation is closely linked to the level of technical sophistication of the infrastructure, which must ensure stable and high-capacity real-time data processing. A key prerequisite for the smooth functioning of virtual and augmented environments is the availability of high-speed connectivity (e.g., 5G), robust server capacities, and specialized hardware such as VR and AR devices. Airlines and airports are therefore facing the need for a major upgrade of their IT systems, including the renewal of data centers, the strengthening of network infrastructure, and the expansion of digital service support. Effective use of the Metaverse in aviation therefore requires not only investment in cutting-edge hardware, but also a strategic approach to building a sustainable and secure technological infrastructure [15].

In addition to innovative opportunities in customer service and process efficiency, Metaverse technologies place high demands on secure data processing. Virtual and augmented realities, digital twins, and blockchain solutions generate vast amounts of sensitive information, from passenger personal data, booking details, and payment transactions to loyalty program data. Every interaction in the digital environment is therefore a potential target for cyber threats. One of the biggest risks is the possibility of unauthorized access or data leaks, which can lead to a loss of customer trust and significant damage to the reputation of airlines. In this context, privacy protection and data security play a key role. Given the growing risks associated with digital technologies, it is clear that ensuring data integrity and protecting privacy will be one of the most important areas of development in the deployment of the Metaverse in aviation. It is therefore essential for companies that want to remain competitive and maintain customer trust to address these challenges proactively and strategically.

The implementation of the Metaverse in the aviation industry brings with it a fundamental transformation not only of technological systems, but also of the working environment and the way employees perform their tasks. One of the main obstacles airlines face is the low level of acceptance of new technologies among employees, especially those with many years of experience with traditional practices. Resistance to change may stem from a fear of losing certainty in established processes, concerns about technological complexity, and a lack of confidence in the effectiveness of new solutions. Another problem is insufficient digital literacy, which makes it difficult to adapt quickly to new systems. For many employees, especially those in operational positions, working with VR or AR technologies is completely new, requiring extensive and often costly training. Complex user interfaces can lead to frustration and reduced motivation to complete training, thereby reducing the effectiveness of Metaverse implementation.

Except technological and organizational challenges, the deployment of VR and AR technologies in the aviation

industry have to face complex legal and regulatory frameworks that companies must strictly adhere to. Given the high safety standards in aviation, any use of new technologies is subject to thorough certification and approval processes by the relevant regulatory authorities. One of the biggest challenges is the need for new VR training, simulation systems, and digital tools to meet official aviation standards and be recognized as equivalent to traditional methodologies.

Another aspect is international regulation, as the aviation industry is regulated by global standards set by organizations such as ICAO (International Civil Aviation Organization) or EASA (European Aviation Safety Agency). Any technological innovation that affects flight safety, crew training, or aircraft maintenance must comply with international regulations. This significantly increases the time required to implement new solutions and raises the costs associated with certification processes. For airlines and aircraft manufacturers, this means that, in addition to technical readiness, they must also invest in legal advice, safety audits, and regulatory cooperation to ensure that their digital transformations are fully compliant with applicable legislation. These legal and regulatory requirements can act as a brake on innovation, but at the same time they are an essential tool for protecting safety and confidence in the global aviation system.

VI. CONCLUSION

The main objective of this study was to highlight the potential of using Metaverse technology in aviation to increase the efficiency of several processes in air transport. The findings confirm that its application can streamline staff training and education, support aircraft maintenance, and improve planning and simulations, ultimately contributing to greater safety and productivity. At the same time, it has been shown that the successful adaptation of these technologies requires appropriate organizational approaches and the gradual development of digital skills within airlines.

Despite optimistic results and practical examples, there are also significant obstacles that could slow down the wider introduction of the metaverse in aviation. One of these is the high initial investment in hardware, such as professional VR headsets and content creation, which not all entities can afford to the same extent. Furthermore, there is a lack of uniform standards and methodologies – from technical platforms to safety and training standards. Regulatory authorities are proceeding cautiously and are only gradually approving the use of VR, for example in pilot training, which means that flight schools and airlines must combine new procedures with traditional ones for the time being. Another challenge is the adaptation of staff to the new working environment, where it is necessary to provide training for employees and address potential problems such as fatigue or nausea during prolonged use of VR. At the same time, if the Metaverse were to offer a full-fledged alternative to some forms of business travel in the future, such as virtual conferences, this could also mean a certain decline in demand for traditional flying for the aviation industry, according to IATA. Last but not least, attention must be paid to cybersecurity and the protection of sensitive data within virtual worlds. The integration of real flight operations with Metaverse platforms will require robust security against attacks and data leaks.

ACKNOWLEDGMENT

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Thermal and Fluid Dynamics Analysis of Hungarian Folk Heating Appliances

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Abstract

Characteristic heating appliances of Hungarian architectural heritage, such as the tiled stove (cserépkályha), a pot-shaped tiled stove (bögrés szemeskályha), and the furnace (kemence), reflect not only architectural history aspects but also their thermal properties in their development and evolution. Since knowledge of these historical heating appliances is largely limited to literary and visual sources, their testing under operational conditions is generally not possible, even with reconstructions. Consequently, the analysis of their thermal and fluid dynamics behaviour is primarily accomplished using CFD simulation (Computational Fluid Dynamics). A previous on-site measurement provides a reliable basis for the simulation, during which the flue gas emissions and temperature data measured at 32 points of a wood-fired tiled stove were recorded. By using the measured firebox temperature curve as a reference, the validation of historical appliances with similar heating and cooling parameters allows for drawing conclusions about the reasons for their design, prevalence, and evolution. Furthermore, the study offers relevant lessons for the design and operation of 21st-century wood-fired appliances. This is particularly significant because in Hungary, biomass, primarily firewood, is the second most common household fuel source. It provides heating for approximately 1 million households, or 4 million people [3], with the majority concentrated in family homes.

Keywords— Hungarian folk architecture, traditional heating appliances, tile stove, pot-shaped tile stove, furnace, CFD simulation, thermal performance, biomass heating, wood-fired appliances, architectural heritage

I. INTRODUCTION

The distinctive heating appliances that are part of Hungarian architectural heritage, such as various types of furnaces (kemence), tiled stoves (cserépkályha), or the stove with mug-like tiles (bögrés szemeskályha), are significant not only from an architectural history, archaeological, or ethnographic research perspective; their thermal properties, among other factors, also played a role in their development and evolution. The purpose of this publication is to outline the developmental history of heating appliances used from the Middle Ages to the mid-20th century, to present their regional differences, while also analyzing their operation from a thermal and fluid dynamics standpoint. The investigation highlights that folk architectural forms are fundamentally determined by available resources, particularly fuel supply and climatic conditions.

II. HISTORICAL OVERVIEW, HISTORY OF DEVELOPMENT

A. Beginnings

The history of Hungarian heating appliances dates back to the pit-houses of the Hungarian Conquest era, where a corner-built furnace, heatable from inside the room, was typical. The 15th century brought a significant change in heating culture with the appearance of smoke-free residential houses. It was during this time that stoves heated from the outside became widespread in rooms, first among the aristocracy and later among the poorer classes as well. An early form of the stove was a further development of the traditional furnace, in which large, bowl- or pot-shaped ceramic elements, so-called "kályhák" (stove with pot-shaped tiles), were built into the thick adobe wall. The name for these structures that became common was bögreszemes kemence (furnace with pot-shaped tiles) or kályhás kemence (stove-like furnace).[9]

B. Tiled Stove

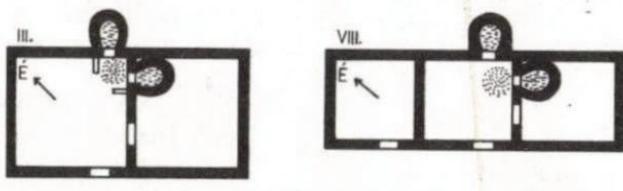
By the 15th century, for the most sophisticated constructions, the technology had undergone significant development. The body of the stove was now constructed from separate, thin ceramic elements—tiles—and plinths, central ledges, and the characteristic stove shoulder appeared. The most important thermal consequence of this structural change was the thinning of the stove wall. [7] Whereas the thick cob wall of earlier furnaces radiated heat slowly and for a long time, here only a single tile-thick ceramic layer separated the firebox from the room to be heated. These tiled stoves were typically built without a backing wall, which enabled much faster heat dissipation to their surroundings.



Tile stove, Southern Transdanubian type, Zselickisfalud, 1931 (Sabján, 2008, p. 64)[7]

C. Furnace

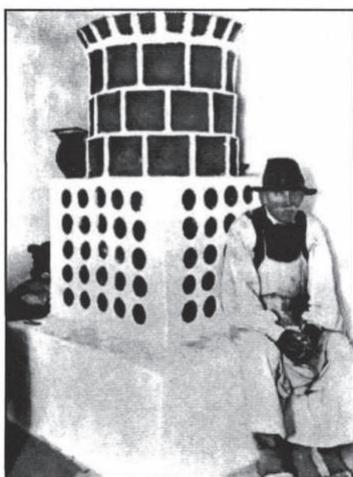
From the 15th-16th centuries, two distinct types of furnaces with different functions emerged: one for heating and one for baking-cooking. Several significant differences can be observed between the two functionally different types. Among the peasantry, the heating furnace in rooms were always furnaces with pot-shaped tiles, meaning their walls were lined with ceramic tiles. [9] It is not yet entirely clear why the use of furnaces with pot-shaped tiles on the Great Hungarian Plain during the 18th century and the more ornate oven was replaced by a simple furnace made of mud, but the reason may be poverty or a decline in the number of master potters. In contrast, ovens used for baking and cooking were never decorated or lined with "pot-shaped." Typical types of ovens used for baking-cooking purposes were the so-called projecting ovens, which protruded from the house's contour, and the so-called summer ovens, built outside the house and used—as their name suggests—during the summer period. [9]



House with projecting furnace [10]

D. Stove with pot-shaped tiles

The stove with pot-shaped tiles was also of medieval origin. In its structure, it represented a transition between ovens and tile stoves, combining the durable heat storage of thick-walled ovens with the rapid heat emission of thin-walled tile stoves. Its lower, square section was built from pot-shaped tiles set into thick, approximately 30 cm mud walls, while its upper, cylindrical part consisted of closely fitted, bowl-shaped ceramic tiles that were in direct contact with the firebox and were fixed together with mud mortar. The stove with pot-shaped tiles thus represents an indispensable stage in the development of Hungarian folk heating appliances. [5]

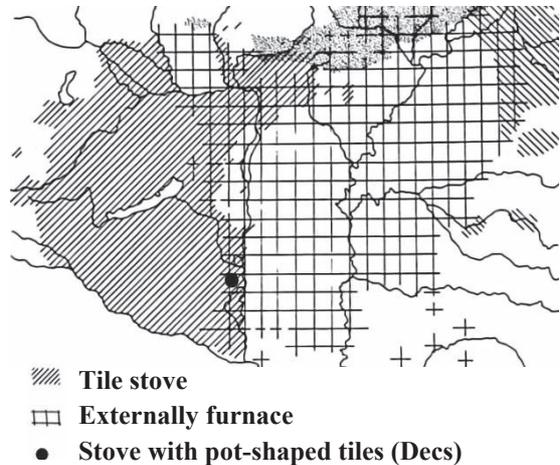


Sárköz stove with pot-shaped tiles, photograph by József Csalagovits, 1934 (Dr. Csalagovits, 1935) [3]

III. GEOGRAPHICAL DISTRIBUTION

By the 20th century, different types of heating appliances had developed distinct regional distributions, which were logically connected not only to building traditions and cultural influences but also to the available fuel. [7]

- In Transdanubia, tile stoves became widespread, where wood burning was dominant in the forested areas.
- In the timber-poor regions of the Great Hungarian Plain, burning straw and other agricultural by-products was available. Here, the externally fired oven became the typical heating appliance.
- The stove with pot-shaped tiles survived the longest at the border between the two major regions, in Decs along the Danube, where both wood and straw were available, thus representing a transition both geographically and functionally between ovens and tile stoves.



IV. STRUCTURAL ANALYSIS

The different functioning of various types is explained by their material and structural characteristics. The differing thermal properties of mud and ceramic tiles (thermal conductivity coefficient, thermal effusivity) fundamentally determine the behavior of structures built from them. [5]

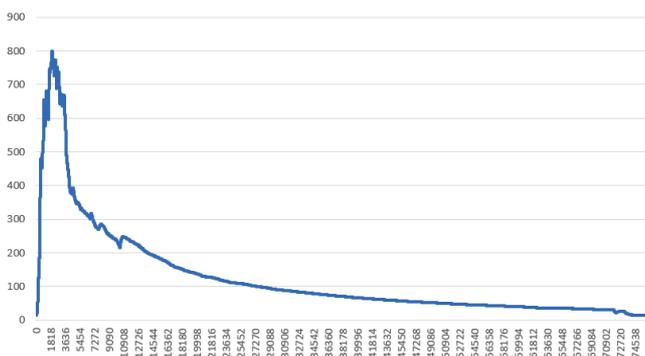
Material Characteristic	Materials	
	Mud	Ceramic tile
Density	900 kg/m ³	2000-2400 kg/m ³
Thermal conductivity coefficient (λ)	0,5-0,7 W/mK	1,0-1,3 W/mK
Heat storage capacity (Specific heat)	0,85-1,4 kJ/kgK	0,84-0,92 kJ/kgK
Volumetric heat storage capacity [kJ/(m ³ ·K)]	891 [kJ/(m ³ ·K)]	1936 [kJ/(m ³ ·K)]
Thermal effusivity	543 J/(m ² √s·K)	1900-2100 J/(m ² √s·K)
Emissivity coefficient	0,91-0,93 (whitewashed wall) 0,85-0,90 (mud)	0,90-0,94 (glazed) 0,85-0,90 (unglazed)

IV. INVESTIGATION: CFD SIMULATION

Since knowledge of these historical heating appliances is largely limited to literary and visual sources, their examination under operational conditions—even in the case of reconstructions—is not generally possible. Therefore, the analysis of their thermal and flow behavior can primarily be achieved through the CFD (Computational Fluid Dynamics) simulation method.

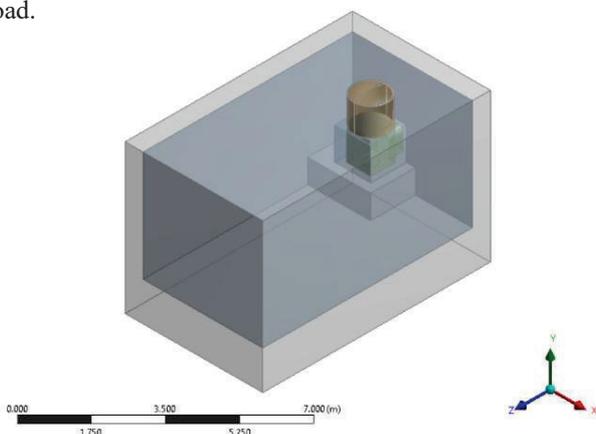
The simulation is based on an on-site measurement, during which the flue gas emissions and temperature data measured at 32 points of a wood-fired stove were recorded. By using the measured firebox temperature curve as a reference, through the examination of historical appliances with similar heating and cooling parameters, we can draw conclusions about the reasons for the emergence, survival, and development of these appliances. During the measurement, the volume flow rate was assumed to be constant throughout.

The measured firebox temperature curve used as the input boundary condition for the simulation. The data series shows the heating and cooling cycle of a real tiled stove, which served as a reference for modeling the behavior of the historical appliances. The maximum measured firebox temperature was ~800°C, and the measurement duration was ~75000 seconds (~21 hours)



Measured firebox temperature curve

Through the thorough examination of a single structure via the stove with pot-shaped tiles, we can gain insight into the essential differences between furnaces and tile stoves, as well as into the process of their developmental divergence. In the simulation, the model was created based on the geometry of the stove with pot-shaped tiles from Decs, but the pot-shaped tiles were not modeled separately in the wall of the lower prism. The investigation analyzes the response of the 30 cm thick mud wall and the tile-thickness ceramic wall to thermal load.

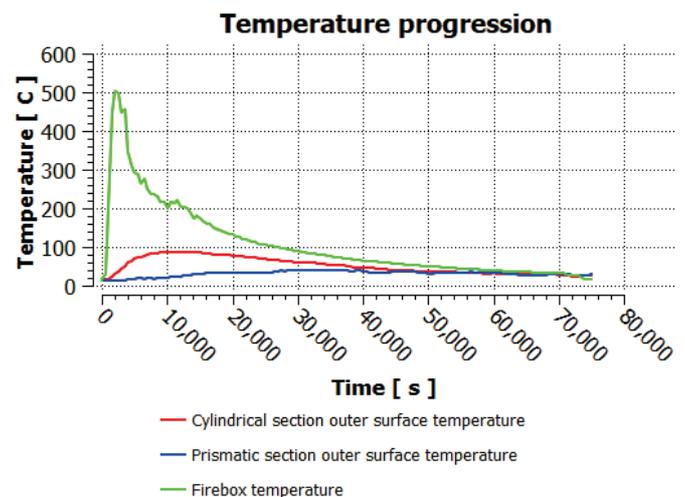


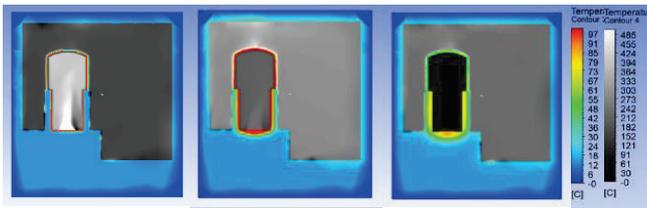
Geometry of the stove with pot-shaped tiles from Decs

The simulation was performed using Ansys CFX software. The computational mesh, created using the Hex dominant method, consisted of domains including the stove walls, the cylindrical upper section, the surrounding air, and the firebox. Heat transfer was described using the Thermal Energy model, and thermal radiation was described using the Monte Carlo method, taking into account 10,000 particle histories. For air, buoyancy was also modeled (Buoyant model). When determining the boundary conditions, the temperature curve from the previous on-site measurement was applied as a time-dependent function at the firebox inlet, with a constant inflow velocity of 1 m/s. The external boundary walls of the examined room were assumed to have a constant temperature of 0 °C, while the stove door was considered as a 15 °C opening.

The thermal effusivity of ceramic tile is approximately 3.5-4 times greater than that of mud, which means faster heat exchange and more dynamic behavior. The higher thermal effusivity ceramic surface reacts quickly to temperature changes, while the lower thermal effusivity mud results in slower, more balanced, and more comfortable heat sensation.

The temperature curves recorded during the examination of the stove with pot-shaped tiles clearly illustrate the dual operating principle of the structure. Following the rapid rise in firebox temperature, the upper, thinner-walled, cylindrical part consisting of ceramic tiles heats up almost immediately and provides rapid, intensive heat emission, similar to tile stoves. In contrast, the lower prism with thick (approximately 30 cm) mud walls absorbs heat significantly more slowly, and its surface temperature remains at a lower level. This massive lower part functions as a huge heat storage mass, which is capable of radiating uniform, comfortable heat to its surroundings for many hours (up to 18-20 hours) after firing has ended, similar to traditional furnaces. It can be seen that although the firebox temperature remains higher than that of the walls almost throughout, the stove walls begin to cool after approximately 10 hours, as the room air cools them to a greater extent.





Simulation results at maximum outer temperature values of temperature curves (at 1.500, 12.000, and 20.000 seconds)

In the simulation results displaying temperature distribution, the solid structural elements (stove and walls) are represented with a color scale, while the gaseous medium (air) is shown in a black-and-white scale. The color scale displays temperature values between 0-100 °C while the black-and-white scale covers a range of 0-500 °C.

The simulation results confirm that the stove with pot-shaped tiles combined the advantages of the two fundamental heating appliance types: the rapid heating capability of tile stoves and the long-lasting heat storage of furnaces. This structural solution enabled the efficient utilization of fuels with different combustion properties and represented an advanced heating technology perfectly adapted to environmental conditions, which is an outstanding example of Hungarian folk architecture.

V. CONCLUSIONS

The current simulation study confirmed the dual operating principle of the stove with pot-shaped tiles; however, further investigations are necessary for a more precise understanding of its heat emission. Future research should aim to quantify the ratio of heat dissipation between the two main parts of the stove body—the lower prism and the upper cylinder—throughout the entire heating cycle. It would be particularly important to analyze how the ratio of heat emitted through radiation and convection changes during the heating and cooling phases. With this data, we could gain a more accurate picture of the extent to which this advanced structure was capable of efficiently burning different types of fuel and dynamically regulating the comfort of the living space.

The spread of different heating appliance types was primarily determined by the nature of available fuel. Since the rapidly released, high heat energy of straw required the enormous heat storage mass of the furnace for absorption and slow release, which was ensured by the thickness of its walls varying between 20-30 cm, the more extreme temperature conditions of the firebox were better balanced. In contrast, for the slower, more evenly burning wood, the smaller mass of the tile stove was sufficient, which in turn provided faster heating, since only a single tile-thickness ceramic layer separated the firebox from the room to be heated.

The ceramic tiles built into the walls of early heating furnaces were not exclusively decorative. They increased the heating surface and, since they were in direct contact with the firebox, their warmer temperature significantly accelerated heat emission, which thus had practical significance only in the case of furnaces used for heating.

It has long been known that the type of heating appliances and their placement directly influenced the floor plan of folk houses. However, baking-cooking furnaces were connected to

the peasant homestead's living space in a different way, because their primary role was heat retention, not heat emission. Since these were used in summer as well, the projecting furnace may have developed to avoid overheating, the great advantage of which was that from spring to autumn, that is, during the warm summer period, it reduced the heat emission of the stove body toward the living space. This same fact explains why summer furnaces were built separately from the house, as their name also reflects: when used in summer, they did not heat up the house during use.

VI. RESULTS: ARCHITECTURAL AND SOCIAL IMPLICATIONS

The results of the investigation go beyond technical-historical curiosities.

The investigation thus highlights that folk architectural forms were not created out of tradition preservation or primarily aesthetic considerations, but developed as a response to available resources (fuel, building materials, expertise) and climatic conditions (summer overheating). Regional differences therefore primarily reflect not cultural isolation, but adaptation and adjustment to the environment.

Based on data from the Hungarian Central Statistical Office, there are approximately 326,000 peasant houses, farmsteads, and other buildings with folk architectural value in Hungary, for which there is a prominent need to preserve the original character of buildings and carry out authentic renovations. This creates significant social demand for the dissemination and promotion of the application of traditional folk heating appliances.[4]

In addition to all this, the investigation also provides relevant lessons for the design and operation of 21st-century wood-fired appliances. This is of particular significance, since in Hungary biomass, primarily firewood, is the second most common household fuel among energy carriers. It provides heating for approximately 1 million households, that is, 4 million people [3], the majority of which is concentrated in the heating of family houses.

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Product Matching with Multimodal Integration for E-Commerce Price Intelligence

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Abstract— Product matching is a fundamental challenge in e-commerce, where the task is to determine whether two product listings from different sources refer to the same real-world item. Accurate identification is essential for price monitoring, stock management, and competitive intelligence, yet traditional approaches based on textual similarity or structured identifiers often struggle with incomplete and heterogeneous data. This paper presents RePrice, a hybrid product matching system that integrates text, attribute, and image similarity within a unified decision pipeline. The approach combines deterministic rules with AI-driven scoring, leveraging semantic embeddings and CLIP-based image features. Experiments on 29,000 product listings from 23 platforms demonstrate that multimodal integration significantly improves performance, achieving an F1-score of 0.75 compared to 0.42 for a text-only baseline. We analyze the contribution of each modality, provide category-level results with error analysis, and discuss the scalability and robustness of the system for real-world e-commerce applications.

Keywords— product matching, price intelligence, machine learning, CLIP, multimodal integration

I. INTRODUCTION

Accurate product matching – the task of determining whether two product listings refer to the same real-world item – is a cornerstone of e-commerce platforms and price intelligence systems. Online marketplaces and comparison services rely on it to merge duplicate entries, consolidate pricing information, and enable competitor monitoring. Without reliable matching, customers may face duplicate or inconsistent listings, while businesses lose the ability to track inventory and benchmark competitors effectively. At the same time, the scale of e-commerce continues to grow rapidly, with global retail sales in the trillions of USD annually, making manual reconciliation infeasible.

The challenge arises from the heterogeneity and incompleteness of e-commerce data. Many listings lack universal identifiers such as GTIN or EAN codes, while product names, descriptions, and attributes are expressed in inconsistent formats across vendors. As a result, naive string-matching techniques often fail to recognize semantically equivalent items. This has motivated the development of more advanced computational approaches to product matching.

Early methods primarily focused on textual similarity, treating the problem as one of document or string matching. However, simple distance metrics struggle with synonymy, abbreviations, or differences in word order. To address this,

recent research has leveraged neural models that encode text into dense semantic embeddings. For example, Gupte et al. proposed a multimodal neural network that jointly models textual and visual signals, showing that richer representations improve matching accuracy [1].

Beyond textual data, structured attributes such as brand, model, size, and specifications can provide strong additional cues. When these fields are present and consistent, they serve as reliable signals for alignment. However, in real-world marketplaces, attributes are often missing or misreported, limiting their utility. Khandelwal et al. addressed this by introducing the MXT framework (Multimodal Adaptation Gate, Xception network, and T5 encoder-decoder) for multimodal attribute extraction, which predicts missing values by leveraging both text and images, even under distant supervision [2]. This demonstrates that structured data can be enriched by multimodal learning to mitigate sparsity.

Another important modality is visual data. Images are particularly valuable in visually driven categories such as fashion or furniture, where appearance is key to product identity. Das et al. introduced the MAPS model (Multimodal Attention for Product Similarity), which fuses product text with image features via multimodal attention to improve cross-category product similarity [3]. These studies highlight the potential of vision–language models to improve robustness in scenarios where textual descriptions alone are ambiguous.

Recent studies also point to the need for strategic evaluation of precision–recall trade-offs in product matching systems. Köpcke et al. argued that optimizing the balance between precision and recall is critical for industrial deployments, where overly aggressive matching can cause false merges, while conservative thresholds can lead to missed duplicates [4]. This perspective emphasizes that effective product matching must be both accurate and adaptable to application-specific requirements.

In this paper, we present RePrice, a hybrid product matching system designed for industrial-scale price intelligence. RePrice integrates semantic text similarity, structured attribute matching, and image-based comparison in a unified decision pipeline. Unlike prior studies that often focus on a single modality or assume well-curated datasets, our contribution lies in demonstrating a scalable and modular architecture that maintains performance under noisy, incomplete, and heterogeneous data. On a large, multi-

category dataset, we show that multimodal integration yields substantial improvements over unimodal baselines, achieving an F1-score of 0.75 compared to 0.42 for text-only matching. In addition, we provide a breakdown of contributions by modality, conduct error analysis, and discuss the implications for deployment in competitor monitoring and dynamic pricing.

The main contributions of this work are summarized as follows:

- **Modular multimodal architecture:** We design a hybrid product matching pipeline that integrates textual, attribute-based, and visual similarity signals, and remains functional even when some modalities are missing.
- **Transparent and tunable decision process:** Unlike end-to-end black-box models, our weighted integration scheme provides interpretability and allows practitioners to adjust the influence of different modalities according to business needs.
- **Robustness under noisy, heterogeneous data:** We demonstrate that the system maintains high precision and recall across categories despite incomplete identifiers, inconsistent attributes, and varying image quality.
- **Practical deployment orientation:** The architecture is implemented as independent microservices, ensuring scalability and ease of maintenance in real-world e-commerce price intelligence scenarios.

II. RELATED WORK

The limitations of unimodal solutions have motivated a diverse body of research that combines different sources of information for product understanding. One important direction integrates textual and visual data. Gupte et al. showed that a multimodal neural network, trained jointly on product descriptions and images, improves inventory reconciliation tasks compared to text-only baselines [1]. Their study highlights that combining modalities helps models generalize across the noisy and heterogeneous inputs typical of e-commerce.

Another significant line of work investigates how generative frameworks can enrich structured product data. Khandelwal et al. introduced MXT, a large-scale generative model for multimodal attribute extraction, which predicts missing values by exploiting both textual and visual cues [2]. This work directly addresses one of the main bottlenecks in product matching: incomplete or inconsistent attributes. By treating attribute inference as a generative task, MXT offers a scalable strategy for enhancing product catalogs without requiring exhaustive manual labeling.

Further research has focused on the robustness of multimodal fusion itself. Javaloy et al. argued that many architectures suffer from modality collapse, where one channel dominates the decision process. To address this, they proposed an impartial optimization training pipeline that balances gradient contributions across modalities, ensuring both visual and textual features contribute meaningfully to the outcome [5]. Their findings underline the importance of fusion design: success depends not only on which modalities are combined, but also on how they are integrated.

From a similarity-learning perspective, Gupte et al. favor a dual-encoder, late-fusion architecture in which text and

image representations are optimized as vectors projected into a shared embedding space. Training is stabilized by a margin-based metric objective (e.g., triplet/contrastive) and in-batch negative sampling, complemented by temperature scaling to calibrate the logits. The resulting embeddings can be queried efficiently in large-scale retrieval tasks using ANN-based indexes (e.g., HNSW/IVF-style search), which is especially important for taxonomy mapping [1].

Ma et al. extended this line of work with hierarchical similarity learning for language-based product image retrieval, showing that modeling multiple representation levels improves the alignment between textual queries and product imagery [6]. Together, these studies demonstrate that multimodal representation learning can bridge heterogeneous modalities and produce robust similarity signals.

Finally, generative approaches have been applied to attribute value extraction. Blume et al. show that prompting-based generative models can recover implicit product attributes that sequence-tagging baselines miss, achieving competitive results on Amazon and MAVE datasets (including multilingual settings) with strong data efficiency—in some cases with as few as two in-context examples [7].

Taken together, these contributions establish a consensus: multimodal integration is essential for robust product matching in e-commerce. Text encoders capture semantics, attributes provide structured anchors, and images add visual distinctiveness, but only their thoughtful combination enables the accuracy, recall, and scalability required in production systems. Building on this foundation, our work contributes a modular pipeline that integrates pre-trained models and deterministic logic, explicitly designed for the noisy and incomplete data of real-world e-commerce.

III. METHODOLOGY

Our RePrice system employs a modular, hybrid pipeline that sequentially integrates multiple similarity signals to determine whether two product listings refer to the same real-world item. Figure 1 illustrates the overall architecture: two listings are processed in parallel through several modules, each producing a normalized similarity score. These outputs are subsequently aggregated by a weighted integration module, which yields the final decision.

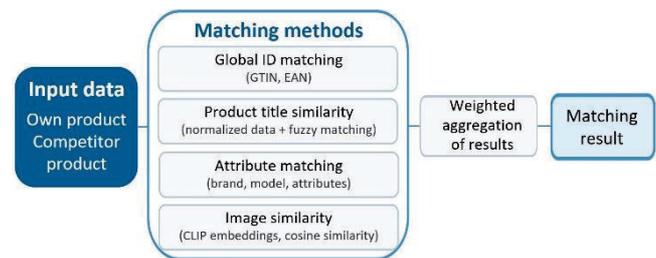


Figure 1. Schematic architecture of the RePrice hybrid product matching pipeline. The system evaluates textual, attribute-based, visual, and price similarity for a pair of product listings, then integrates these signals through weighted aggregation to produce a match decision.

Identifier Matching: The pipeline begins with structured identifiers such as GTIN, EAN, UPC, or ISBN codes. In theory, these unique identifiers provide near-perfect matching when available. In practice, however, public e-commerce feeds rarely include such codes, and sellers often omit them [8]. As a fallback, manufacturer-specific identifiers such as

model numbers or part codes are extracted from structured fields or parsed from product titles. These identifiers are most common in technical categories such as consumer electronics, while they are usually absent in fashion or home goods. When a unique identifier match is found, RePrice assigns a high-confidence match. However, as identifiers cover only a small fraction of listings, this module alone yields limited recall.

Product Name Similarity: Since all listings include titles, textual similarity between product names provides the broadest coverage. Titles are normalized by lowercasing, removing stopwords and punctuation, and standardizing numeric tokens. RePrice computes fuzzy similarity by combining token-level overlap and edit distance. To improve robustness, domain-specific preprocessing is applied, such as splitting concatenated codes and expanding abbreviations.

While lexical similarity captures many straightforward matches, it struggles with semantic variation (e.g., synonyms, abbreviations, and word-order changes). Transformer-based language models such as BERT [9] encode semantic equivalence more effectively, though at the cost of higher computation and training requirements. In our experiments, well-tuned string-matching baselines recovered only ~35–40% of known matches, which is consistent with the survey’s qualitative finding that purely lexical approaches underperform on heterogeneous, noisy data [10].

Attribute and Feature Matching: Structured attributes provide complementary evidence. Depending on the category, relevant attributes may include brand, size, color, memory specifications, or packaging details. RePrice extracts and standardizes available attributes from both listings. Categorical fields (e.g., brand, color) are compared for exact matches or synonym equivalence, while numeric attributes (e.g., weight, price) are compared within tolerance intervals.

Consistent with Gal’s tutorial on entity resolution in the big-data era [11], attribute-based signals can substantially improve recall when attributes are reliable, expanding match coverage over name-only baselines. However, missing or noisy attributes can introduce false positives; thus, RePrice assigns greater weight only to distinctive attributes (e.g., exact model numbers), while common attributes such as color or approximate price are treated as weaker signals.

Image Similarity: Visual information is especially valuable in categories where appearance is critical, such as fashion or furniture. For each listing, the primary product image is preprocessed (resized, background trimmed) and encoded using CLIP [12], a vision–language model trained on large-scale image–text pairs. The resulting embeddings are compared using cosine similarity.

Decision thresholds are not fixed a priori; we calibrate them on a held-out validation split to maximize F1 under a precision constraint. In our study, the resulting operating points were 0.85 for a strong positive match, 0.70–0.85 for an uncertain region, and below 0.70 for a negative decision. These numeric cutoffs are dataset-specific. Our procedure is analogous to threshold calibration practices in image retrieval, where dataset-aligned operating points are tuned based on retrieval metrics such as mean Average Precision (mAP) [14].

Weighted Integration: After computing the similarity scores from identifiers, titles, attributes, and images, the integration module produces a final confidence score via weighted aggregation. The weighting scheme prioritizes high-

precision signals (e.g., identifier matches) while still leveraging strong textual or visual evidence when identifiers are absent. Formally, if the individual similarity scores are denoted as

- s_{ID} ,
- s_{Name} ,
- s_{Attr} ,
- s_{Img} , and
- s_{Price} ,

they correspond respectively to the following modules: identifier matching, product name similarity, attribute similarity, image similarity, and price similarity. The final confidence score s_{final} is defined as:

$$s_{final} = 0.40s_{ID} + 0.20s_{Name} + 0.10s_{Attr} + 0.20s_{Img} + 0.10s_{Price}.$$

Pairs exceeding the decision threshold (set near 0.5 on the validation set) are labeled as matches; those below are non-matches; and borderline cases may be flagged for manual review. This transparent, rule-based ensemble reflects practical considerations in industrial systems, where interpretability and tunability are as important as accuracy. Future work may extend this integration step with data-driven weight optimization, for example via learning-to-rank frameworks.

The weight distribution of the similarity modules is summarized in Table 1.

Table 1. Weight distribution of similarity modules in the RePrice integration model.

Matching Approach	Weight
GTIN/EAN match	40%
Product name similarity	20%
Image hash similarity	20%
Price proximity	10%
Attribute similarity	10%

In practice, each similarity module outputs a normalized score between 0 and 1. When one or more modalities are missing (for example, when an image or attribute field is unavailable), the remaining scores are automatically reweighted so that the final confidence value remains comparable across listings. The decision thresholds were tuned on a held-out validation set to balance precision and recall. This calibration ensures that the fusion behaves consistently across categories and clarifies how the weighted integration operates in practice.

IV. EXPERIMENTS AND RESULTS

We evaluated the RePrice system on a large-scale dataset collected from 23 e-commerce platforms. The dataset contains approximately 29,000 product listings across diverse categories, including electronics, apparel, fast-moving consumer goods (FMCG), and home appliances. To establish a reliable ground truth, 5,200 verified matching pairs were identified using manual annotation and trusted identifiers.

This labeled set served as the benchmark for measuring precision, recall, and F1-score.

To assess performance, we first considered unimodal baselines before turning to the hybrid pipeline. Using fuzzy string similarity on product titles alone produced a precision of 0.37, recall of 0.49, and an F1-score of 0.42, which is consistent with prior findings that string-based approaches struggle in noisy product data [15]. The full RePrice system, by contrast, achieved a precision of 0.86 and recall of 0.66, yielding an F1-score of 0.75. This represents a substantial improvement, more than halving the error rate relative to the text-only baseline and clearly demonstrating the benefit of combining multiple modalities [16]. The comparison between the baseline and the hybrid system is shown in Table 2.

Table 2. Performance comparison of unimodal and hybrid approaches.

Method	Precision	Recall	F1-score
Title-only (fuzzy)	0.37	0.49	0.42
RePrice (hybrid)	0.86	0.66	0.75

When results are broken down by product category, important differences emerge. In the electronics category, multimodal integration substantially reduced false positives when both specifications and images aligned, and recall improved even in the absence of explicit model numbers. Apparel showed even larger relative gains in recall, since textual descriptions are often vague or inconsistent; here, visual embeddings provided decisive confirmation of matches that text-based modules would have missed. FMCG products exhibited more modest improvements because naming conventions are relatively standardized, though multimodal signals still reduced misses when one listing omitted key details. Home appliances showed performance patterns similar to electronics, with attributes and images contributing strongly, though in a few cases visually similar appliance models lacking textual detail led to false positives. Across all domains, the system maintained high precision (above 0.85), while recall varied with the degree of data heterogeneity.

An error analysis provided further insight into system limitations. False negatives most often occurred when product titles shared no tokens and other modalities were unavailable; in such cases, the hybrid pipeline had little evidence to rely on. False positives tended to arise when two products differed only in minor specifications, such as memory size, but shared highly similar names and images. These outcomes mirror known difficulties in entity resolution, where near-duplicate records challenge automated methods. Additional errors were observed when sellers reused identical stock photos across product variants, leading the image module to assign high similarity scores despite underlying differences. Price information helped mitigate some mistakes, as large discrepancies often signaled mismatches, though reliance on price alone remained unreliable since identical items can vary in cost across sellers.

To measure the contribution of each module, we conducted ablation experiments. Removing the image similarity step reduced recall dramatically in apparel, where many matches depended on visual evidence. Excluding attribute matching increased false positives, particularly for

products with variants, as the system could no longer verify critical distinctions. Omitting price checks had only a minor impact on overall F1, but slightly raised the false positive rate by failing to catch implausible price mismatches. These results underscore that each modality contributes in complementary ways: text provides broad coverage, attributes and price refine candidate pairs, and images supply crucial confirmation in ambiguous cases [11].

Taken together, these experiments confirm that the hybrid pipeline significantly outperforms unimodal baselines. A precision of 0.86 ensures that identified matches can be trusted for downstream applications, while a recall of 0.66 substantially reduces manual workload by automatically identifying two-thirds of true matches. The modular design further ensures adaptability to different product categories and robustness under the noisy, incomplete conditions characteristic of real-world e-commerce data.

To further analyze system performance, representative false-positive and false-negative cases were reviewed to identify recurring error patterns. The most frequent false positives occurred when products differed only by a minor variant - for example, the same smartphone model with different memory sizes - but shared nearly identical titles and images. False negatives were mainly caused by large variations in product naming or by the reuse of identical stock photos across multiple items. For instance, “*Smartphone X 8 GB*” and “*Smartphone X 16 GB*” were incorrectly merged because of identical images, while two color variants of a sneaker (“*Midnight Blue*” vs. “*Dark Navy*”) were missed due to differing descriptive terms. Another common case involved a detergent pack labeled “*6 × 330 ml*” versus “*330 ml*”, which failed to match because of missing pack-size attributes. To address these issues, the system was adjusted to reduce the influence of image similarity when key attributes conflict, incorporate color-synonym normalization, and apply a consistency check for identical stock photos.

V. DISCUSSION

The experimental results demonstrate that multimodal integration substantially improves product matching performance. By leveraging text, structured attributes, and visual signals, the RePrice system compensates for the weaknesses of any single modality. Textual similarity alone proved highly sensitive to noisy or abbreviated product names, yet the addition of attribute comparison and image embeddings enabled correct resolution of many otherwise ambiguous cases. This outcome confirms a broader insight in entity resolution: hybrid pipelines achieve robustness in noisy, heterogeneous environments that unimodal methods cannot [8, 11].

From a practical standpoint, the pipeline provides a reliable foundation for price intelligence and related applications. High precision (exceeding 85%) ensures that automated repricing engines or competitive analytics are based on correct product equivalences, avoiding costly misalignments. Equally important is the system’s modular design, which allows independent operation of each component and facilitates extensibility. New modules, such as category consistency checks or review-based comparisons, can be integrated without altering the overall structure. Moreover, the pipeline remains operational when certain modalities are missing; for instance, if no images are available, the text and attribute modules continue to function.

This flexibility contrasts with end-to-end neural models, which often degrade when input modalities are absent.

The modular architecture is designed for high-throughput operation in production settings, with text, attribute, and image modules running in parallel microservices and their outputs combined via weighted aggregation. This design aims to reduce latency and simplify maintenance in real-world deployments. Furthermore, the weighted scoring scheme provides interpretability: practitioners can inspect the contribution of each modality to individual decisions, which strengthens business trust in the system’s outputs [10].

Despite these advantages, limitations remain. The current integration uses heuristic weights that may not be optimal for all categories. A natural extension is to replace the static weighting with a learned integration model, such as logistic regression or lightweight neural networks trained on labeled matches [13]. Such an approach could capture interactions between signals more effectively—for example, an image match is more convincing when the brand also matches. Another limitation is that the image comparison relies on a general-purpose CLIP model [12] without domain-specific fine-tuning. While this provides robustness, fine-tuning on product-specific datasets might improve discrimination in borderline cases, though at the risk of overfitting to spurious details.

Certain categories of mismatches remain particularly challenging. Subtle differences between nearly identical products, such as model variants with minimal specification changes, can mislead the system. Errors may also occur when identical stock photos are reused for multiple items, inflating image similarity scores. Selective human-in-the-loop review for ambiguous cases, as explored in other hybrid decision frameworks [4], offers a promising solution. By flagging borderline pairs, the system can combine automated efficiency with near-perfect human validation when necessary.

Beyond price intelligence, the RePrice architecture is broadly applicable to other e-commerce tasks, such as assortment de-duplication or catalog unification. Similar multi-signal approaches have been reported in industry deployments, underscoring the practical relevance of multimodal matching [2, 3]. A key advantage of our approach is maintainability: because components are modular, they can be updated independently as data formats evolve or new technologies emerge. This ensures adaptability in the dynamic landscape of online retail.

In summary, the discussion highlights that multimodal integration not only delivers strong empirical results but also supports scalability, explainability, and flexibility in real-world deployment. While limitations persist, particularly regarding static weighting and subtle product distinctions, these challenges point directly to future improvements, including learnable integration and domain-specific tuning.

VI. CONCLUSION AND FUTURE WORK

We have presented RePrice, a practical hybrid system for product matching in the context of e-commerce price intelligence. The study compared three major modalities—textual descriptions, structured attributes, and product images—and demonstrated that each contributes unique strengths to the matching process. Text-based methods alone provided reasonably high precision but often missed matches due to naming inconsistencies or abbreviations. Attribute-

based techniques yielded a more balanced performance but relied heavily on the availability of complete and consistent data fields. Image-based matching, enabled by vision-language embeddings, proved highly effective in visually distinctive domains, adding significant recall in cases where appearance was the key identifier. By integrating all three approaches into a unified decision pipeline, the RePrice system achieved the best overall results, confirming that multimodal integration can compensate for individual weaknesses and deliver robust performance under real-world conditions. The deployed system has already demonstrated value in large-scale e-commerce scenarios, enabling accurate product and price tracking across multiple platforms. These results indicate that a carefully engineered multimodal framework - combining deterministic logic with learned embeddings - can meet the accuracy requirements of modern e-commerce price intelligence while remaining practical to operate at scale.

For future work, we plan to explore learning-based enhancements to the integration layer. In the current system, the combination weights for different modules were set heuristically; an important extension is to use a supervised learning approach to optimize these weights or even replace the weighted sum with a trained model. Approaches such as logistic regression or gradient boosting classifiers could be trained on labeled match versus non-match pairs to automatically calibrate the contribution of each signal. This would improve adaptability across product categories and data distributions. We are also interested in incorporating additional modalities, such as richer textual descriptions or user reviews, which might provide disambiguating information for challenging cases (for example, distinguishing product versions by details mentioned only in long-form descriptions). Finally, refining the image-matching module with domain-specific fine-tuning or higher-resolution models could yield further gains in recall.

In conclusion, our work reinforces the notion that a carefully engineered multimodal framework—combining deterministic logic with learned embeddings—can achieve high accuracy in product matching and meet the demands of modern e-commerce applications.

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Design and transmission of data structures for industrial robots in digitized industrial systems

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Abstract—The increasing integration of industrial robots into digitized manufacturing systems requires unified, lightweight, and vendor-independent data models. Existing frameworks such as the OPC UA Companion Specification for Robotics offer rich semantics and interoperability but are computationally intensive, while MQTT-based approaches provide simplicity and speed at the cost of structure and meaning. This paper proposes the Sparkplug Robotics Profile v1, a lightweight extension to the Sparkplug B standard that bridges this gap by introducing robot-specific semantics and state management within an event-driven MQTT architecture. The proposed model defines structured telemetry (RobotData), command (RobotCmd), and lifecycle (RobotBirth) message types using Google Protocol Buffers for efficient transmission and consistent interpretation across platforms. This approach enables real-time data exchange, scalable multi-robot coordination, and native compatibility with XR-based digital-twin environments. The results highlight that Sparkplug Robotics Profile v1 preserves the simplicity of MQTT while providing semantic depth comparable to OPC UA, facilitating interoperable and resource-efficient robot connectivity from edge to cloud.

Index Terms—Industrial robotics, data models, OPC UA, MQTT, Sparkplug B, digital twin, XR systems.

I. INTRODUCTION

The evolution of Industry 4.0 has transformed industrial robots from isolated automation units into fully integrated cyber-physical systems that continuously ex-

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change information with manufacturing execution, planning, and visualization platforms [1]. As industrial environments become increasingly data-driven, the need for standardized, real-time, and semantically rich data exchange between robots and supervisory systems has intensified.

Traditional robot communication frameworks are highly vendor-specific, relying on proprietary APIs or fieldbus extensions that hinder interoperability. To address this, the OPC UA Companion Specification for Robotics provides a comprehensive object-oriented model for describing robot kinematics, states, and control entities [2]. While this standard enables strong interoperability and alignment with higher-level industrial information models, its complexity and resource demands make it less suitable for lightweight edge or extended-reality (XR) applications [3].

At the opposite end of the spectrum, MQTT-based communication—particularly the Eclipse Sparkplug B specification—offers a simple, event-driven architecture that efficiently transmits process data in near real time. However, it lacks the domain semantics required to describe robotic systems meaningfully. Consequently, an architectural gap persists between semantic richness and communication efficiency.

This research introduces a new, intermediate approach that combines the strengths of both paradigms: the Sparkplug Robotics Profile v1. The proposed profile defines a robot-specific data structure within the Sparkplug B framework, enabling real-time telemetry, command execution, and lifecycle monitoring in a unified namespace. The objective is to support scalable, manufacturer-independent robot integration across industrial, edge, and XR contexts while maintaining low latency and minimal computational overhead.

II. OPC UA COMPANION SPECIFICATION FOR ROBOTICS

The OPC Unified Architecture (OPC UA) is one of the most important industry standards for vendor-independent data communication, based on an object-oriented model and hierarchical address space [4]. The Companion Specification for Robotics, published by the OPC Foundation and the VDMA in 2019, aims to provide a unified description of the states, kinematics, and control parameters of robots, in particular industrial arm robots. In the model, each robot appears as a component, a RobotType object derived from a DeviceType.

It includes:

- identification and metadata objects (Identification, Vendor, FirmwareVersion)
- robot kinematic structure (Axes, Joint, ToolFrame, BaseFrame)
- State and diagnostic information (StateMachine, MotionDeviceSystemState, SafetyState)
- control and programming entities (Program, Task, MotionJob, ProgramState)

The Companion Specification aims to ensure that the data link between the robot and the controller works in accordance with the concepts of Device Integration and Machine Information Model, allowing interoperability with MES/SCADA systems and other OPC UA devices. The descriptive model supports multi-axis kinematics, coordinate transformations, safety state retrieval, and unified handling of fault code objects. Although the Companion Specification is very detailed and industry-wide, its implementation complexity is significant. An entire OPC UA Robotics server stack contains hundreds of NodeId, type definitions and references. Mapping the entire hierarchy of the model is computationally and memory intensive, especially on edge devices or XR-based digital twins where latency and processing capacity are limited [5]. The benefits of the standard - transparency, formalised structure, functional safety compliance - are mainly for factory-level integrations, but it is proving too cumbersome for lightweight edge and real-time monitoring tasks.

III. THE NEED FOR SIMPLIFICATION AND THE ARCHITECTURAL GAP

In robotic data modelling today, there is a dichotomy: OPC UA-based systems offer rich semantics but are complex and resource-intensive; in contrast, MQTT-based solutions such as Sparkplug B are lightweight, fast but poor semantically. Currently, there is no overlap between the two paradigms, which hinders unified edge-to-cloud communication. In OPC UA Robotics, all robot, controller, program, axis relations are represented by explicit node references, and communication is client/server. This is deterministic, but difficult to

scale when hundreds of robots need to transmit data to a cloud or XR system simultaneously. MQTT, on the other hand, uses a publish/subscribe architecture that natively supports asynchronous data flow, but has no common data model - messages are just topics and payloads. Developments towards digital twins, predictive maintenance and XR visualisation require robot data to be available in real time, with low latency and in a manufacturer-independent way. This cannot be achieved by the classical OPC UA model due to node-level query logic, especially when data flows through a central broker or distributed edge network.

The architectural gap is therefore between semantics and speed:

- OPC UA provides meaning but loses lightness,
- MQTT provides speed, but loses reporting,

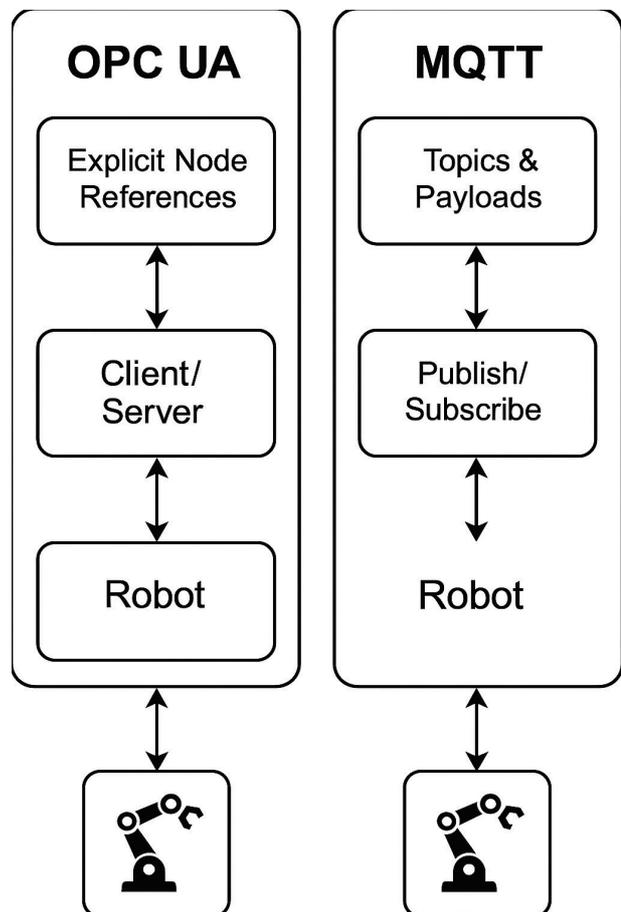


Fig. 1. OPCUA and MQTT protocols

This creates the need for a new, intermediate approach, a lightweight data model that preserves Sparkplug's event-driven, broker-based architecture, but in-

cludes robot-specific metrics and states - the basis of the Sparkplug Robotics Profile v1 concept.

IV. MQTT SPARKPLUG - A LIGHTWEIGHT, EVENT-DRIVEN INDUSTRIAL DATA MODEL

The Message Queuing Telemetry Transport (MQTT) protocol is the de facto standard for lightweight, reliable and asynchronous data transmission in industrial IoT systems [6]. The basic principle of MQTT is message-centric, publish/subscribe communication, which uses a central broker to implement loose coupling between devices. Traditional MQTT applications, however, do not define a uniform data structure or state management; each vendor uses its own topic names and JSON payloads, leading to interoperability problems in the long run [7].

This shortcoming is addressed by the Eclipse Sparkplug standard, developed as part of the Eclipse Foundation Tahu Project and now captured in the Sparkplug Specification v2.2 standard document.

- 1. Unified payload format - transmits raw data in a binary Google Protocol Buffers (Protobuf) format, where each metric is associated with a type, quality flag and timestamp.
- 2. Event-driven state machine - the lifecycle of devices is described by Birth and Death messages and the MQTT Last Will and Testament mechanism. This allows the system to detect when a device has failed, rebooted or lost connection.

Sparkplug's message structure is based on three main hierarchical levels:

```
spBv1.0/<Group_ID>/
  <Message_Type>/
  <Edge_Node_ID>/
  <Device_ID>
```

This enables the creation of a Unified Namespace in which messages are organised thematically and logically, and data can be interpreted independently of the producer. The specification does not define domain-specific data models: a "metric" can be any name-value pair, so it lacks the semantic layer needed for robotics, for example. This gap justifies the introduction of a Sparkplug extension that specifically unifies the data structure and command system for industrial robots.

V. SPARKPLUG ROBOTICS PROFILE V1 - PROPOSED EXTENSION

The Sparkplug Robotics Profile v1 aims to formulate a lightweight, vendor-independent data model for industrial robots that fits the Sparkplug B framework but has extensive robot-specific semantics. The proposed profile is not intended to replace the OPC UA Robotics specification, but to provide an edge-level alternative

optimized for real-time telemetry and XR/digital twin applications.

The profile defines three main message types:

- RobotBirth – publishing metadata and schema versions (model, manufacturer, axle number, frame definitions)
- RobotData – continuous telemetry data (positions, speeds, statuses)
- RobotCmd – non real-time commands and configuration instructions

```
message RobotData {
  uint64 timestamp = 1;
  repeated double joint_pos = 2;
  repeated double joint_vel = 3;
  Pose tcp_pose = 4;
  string mode = 5; // AUTO, MANUAL, TEACH
  string run_state = 6; // RUN, FAULT
  string safety_state = 7; // NORMAL, STOP
  string fault_code = 8;
  double energy_Wh = 9;
  double cycle_time_ms = 10;
}
```

The Pose structure gives the TCP position in quaternions (x,y,z,qw,qx,qy,qz), which facilitates direct spatial mapping of XR systems.

The profile follows the original Sparkplug B pattern, but extends it at the device-level:

```
spBv1.0/RobotCell/NBIRTH/Edge1/RobotA
spBv1.0/RobotCell/DDATA/Edge1/RobotA
spBv1.0/RobotCell/DCMD/Edge1/RobotA
```

This ensures that multiple robots (e.g. RobotA, RobotB) and multiple edge nodes (e.g. Edge1, Edge2) can be coherently managed in the same namespace.

Typical examples of RobotCmd messages:

```
load_job(name)
start_job()
stop_job()
ack_fault()
set_mode(AUTO|MAN)
set_speed_override(percent)
```

The introduction of Sparkplug Robotics Profile v1 does not require firmware modifications to existing robot controllers. A middleware layer (gateway) interfaces the manufacturer-specific APIs (FANUC, ABB, KUKA, UR) to the Sparkplug message structure [8].

VI. RESULTS AND FUTURE WORK

One of the key benefits of the concept is that Sparkplug-based communication is easier to implement

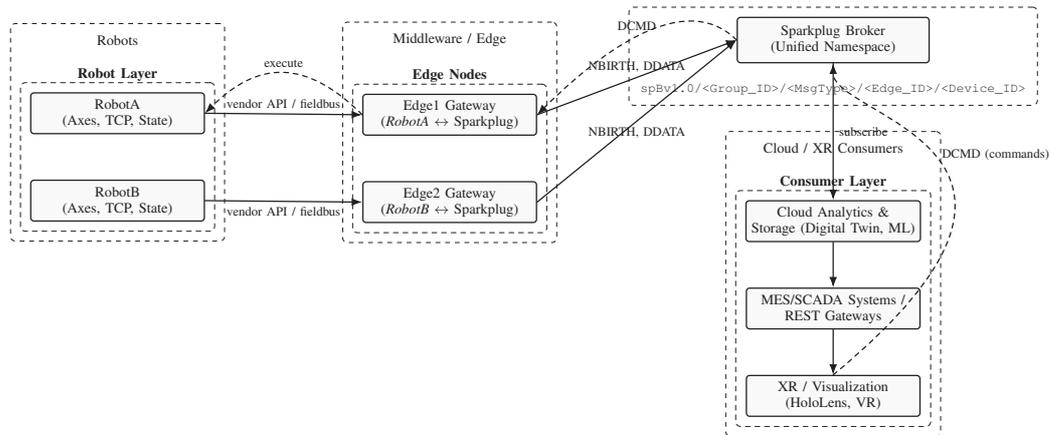


Fig. 2. Sparkplug Robotics Profile data flow: Robot → Middleware → Broker ↓ Cloud/XR. The consumer layer is placed below the broker to maintain full-page width while preserving logical data direction.

on edge devices compared to traditional OPC UA servers, while maintaining industry interoperability. The structure of the profile allowed robots from different manufacturers to appear in a single namespace and to retrieve control and diagnostic data in a common format.

The introduction of Sparkplug Robotics Profile v1 offers new value on several levels:

- At the industrial level: a unified data profile in the MQTT ecosystem, directly usable for robot monitoring, SCADA and digital twin applications.
- At the developer level: a simple, extensible message schema that allows new metrics or commands to be added while maintaining compatibility.
- At the scientific level: the concept provides a transparent, reproducible framework for comparative study and modelling of robotic data transmission.

Further work will focus on three key areas:

- Formal schema standardization: Mapping the current field list into an RFC-like document, and consultation with the Eclipse Sparkplug Working Group community.
- Full interoperability: Testing the profile on robot controllers from different vendors and developing an automatic data mapping between Sparkplug and OPC UA models.
- Digital twin integration: Development of XR and MES-level integrations based on Sparkplug Robotics Profile data, which can be validated in real-time manufacturing environments.

VII. CONCLUSION

The aim of the research was to bridge the gap between the complex but detailed model of the OPC UA Companion Specification for Robotics and the lightweight event-driven architecture of MQTT Sparkplug. The presented

Sparkplug Robotics Profile v1 provides an intermediate solution that provides unified semantics, real-time transmission and vendor independence for robotic data exchange. The solution simplifies the integration of heterogeneous robot fleets from an industrial perspective.

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Embedded Architecture for Simultaneous Analog Signal Processing

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Abstract- The efficient processing of multiple analog signals in real time is a critical challenge in modern electronic systems, particularly in applications requiring high bandwidth, low latency, and low power consumption. This paper presents a comparative study of electronics architectures for simultaneous analog signal processing, with a focus on the conceptual design trade-offs between digital, analog, and hybrid approaches. Several implementation strategies are evaluated, including FPGA-based reconfigurable digital logic, FPAA-based adaptive analog computation, microcontroller-centric designs with integrated peripherals, and mixed architectures combining analog multiplexers, comparators, ADCs, and DACs. The analysis highlights the strengths and limitations of each paradigm. The results underline the importance of selecting architecture according to system-level requirements and suggest future directions for hybrid reconfigurable platforms that combine the programmability of digital logic with the efficiency of analog signal domains.

Keywords - *electronics architecture, analog signal design, hybrid system design, mixed-signal systems, simultaneous analog processing, high-speed electronics*

I. INTRODUCTION

The simultaneous real-time processing of analog signals has become a fundamental requirement in modern electronic systems, underpinning applications as diverse as sensor networks, biomedical instrumentation, advanced signal processing platforms, and industrial automation and control. Although digital technologies dominate contemporary system design, information originating from the physical environment is intrinsically analog in nature. As a consequence, the efficient and precise handling of analog signals remains a critical enabler of system performance. The central challenge lies in developing architectures capable of managing multi-channel, concurrent analog signals while simultaneously satisfying demanding constraints on bandwidth, latency, signal integrity, and energy efficiency.

A broad spectrum of architectural paradigms has been proposed to meet these requirements. Field-Programmable Gate Arrays (FPGAs) offer extensive parallelism, reconfigurability, and scalability, making them attractive for high-performance applications; however, they often incur significant power consumption and resource costs [1-3]. Digital Signal Processors (DSPs) provide specialized computational cores optimized for real-time signal processing, delivering high precision and efficiency for numerically intensive tasks such

as filtering, spectral analysis, and adaptive algorithms. DSP-based solutions are particularly advantageous in multi-channel systems requiring complex algorithmic processing [4-6]. By contrast, Field-Programmable Analog Arrays (FPAAs) provide configurability directly in the analog domain, thereby enabling portions of signal processing to be performed without conversion to the digital domain. Nevertheless, their applicability is limited by device availability, resolution, and precision constraints [7-9]. Microcontroller-based solutions present highly integrated and cost-efficient platforms, yet their processing capacity is inherently restricted in scenarios involving high-speed, multi-channel data streams [10], [11].

Beyond these approaches, hybrid architectures – which integrate analog multiplexers, comparators, analog-to-digital converters (ADCs), and digital-to-analog converters (DACs) – have emerged as compelling alternatives that seek to exploit the complementary strengths of digital and analog subsystems. Such architectures can be tailored to specific application domains, enabling balanced trade-offs between accuracy, throughput, scalability, and power efficiency [12], [13].

This paper aims to provide a systematic assessment of these conceptual design strategies. We present a comparative analysis of FPGA-, FPAA-, and microcontroller-based solutions alongside hybrid analog–digital configurations. The evaluation emphasizes their relative strengths, inherent limitations, and practical deployment scenarios [14], [15]. On this basis, the discussion highlights design considerations that can inform the selection of the most suitable architecture for a given application domain and outlines prospective research directions in the development of reconfigurable hybrid platforms [16 - 18].

II. PARALLEL SIGNAL PROCESSING ARCHITECTURES

A. FPGA based architecture

True parallel data processing can be achieved using FPGA technology. The manufacturing process of FPGAs is optimized for digital logic, whereas the technology used for analog circuits (such as precision ADCs) is different. In the vast majority of FPGAs, either there is no ADC at all, or only one or two low-speed built-in ADCs are available (e.g., Xilinx Zynq-7010/7020 or Intel Altera MAX 10). These are insufficient for $n \times 10$ channels and simultaneous sampling; they are suitable only for auxiliary functions.

To achieve true parallelism, each sensor must be connected to a dedicated ADC, eliminating multiplexing delay. For precise synchronization, a common sampling clock can be distributed to all ADCs – see Fig. 1. The FPGA can perform simultaneous (pre)processing of the digitized signals, such as filtering, FFT, or fault detection.

Entry-level FPGAs (such as the Lattice iCE40, Gowin GW1N, or Xilinx Spartan-7) are available for around 5 – 130 USD, but they require separate ADCs. An 8-channel ADC capable of simultaneous sampling (e.g., AD7606-8, LTC1859) costs approximately USD 35–60 depending on the type. For example, 40 sensors would require 5 such ICs, costing at least USD 175. Solutions with fewer channels can use multiple smaller, cheaper ADCs that can be triggered simultaneously (e.g., ADS8320).

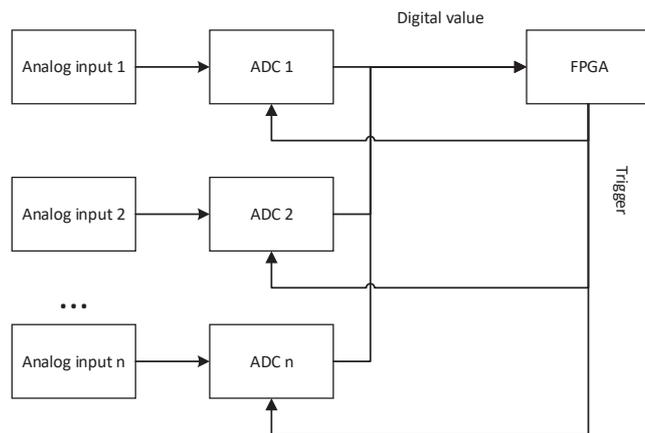


Figure 1: Parallel ADCs for simultaneous signal processing

B. DSP based architecture

Digital Signal Processors are specialized microprocessors designed specifically for high-speed numerical computation and real-time signal processing tasks. Unlike general-purpose MCUs, which are optimized for control logic and peripheral management, DSPs are architected to execute complex mathematical operations – such as multiplication engines, Direct Memory Access controllers, and hardware accelerators for Fast Fourier Transform or digital filtering operations. – extremely efficiently. These components enable deterministic, low-latency data processing with minimal CPU overhead.

DSPs often integrate high-performance ADC peripherals capable of a few channels of simultaneous sampling, synchronized triggering, and direct data streaming to memory or processing units. This makes them well suited for applications that demand precise timing and fast response, such as motor control, audio and image processing, vibration analysis, and real-time communications.

Compared to MCU and DSP analog to digital conversion capabilities, DSP offer higher sampling speeds, lower jitter, and tighter integration with signal-processing pipelines – see the details in Table 1. However, they tend to be more expensive and power-hungry, and they require more specialized programming skills. In both cases, an architecture similar to FPGA is required.

	DSP ADC Peripheral	MCU ADC Peripheral
Sampling speed	Very high (up to 10–100 MS/s)	Moderate (typically 0.1–2 MS/s)
Resolution	12–16 bit, stable even at high speed	Typically 10–12 bit, sometimes 16 bit but at lower speed
Parallel channels	Multiple true simultaneous sampling channels	Usually multiplexed, not truly parallel
Data transfer	Direct DMA access, pipelined data path	Often CPU-driven readout, slower data path
Synchronization	Supports multiple ADCs and external triggering	Limited, often only software-based
Signal-processing integration	ADC tightly coupled with MAC/FFT units for real-time processing	ADC acts only as a data source; processing done by CPU
Determinism / jitter	Hardware-level deterministic timing	Affected by interrupt handling, higher jitter
Target applications	Signal and image processing, control, communications	General-purpose measurement and control tasks

Table 1: Comparison of DSP and MCU analog-to-digital converter

C. FPAA based architecture

The FPAA offers an alternative for parallel processing of multiple analog signals and for creating dynamic signal-processing topologies. However, FPAAs are typically more of a complementary or specialized solution alongside MCU/DSP/FPGA systems rather than a full replacement for them. They are also well-suited for analog pre-processing to reduce power consumption.

In an FPAA, instead of logic gates, analog blocks (amplifiers, filters, comparators, integrators, switches, etc.) can be programmatically interconnected, allowing part of the signal processing to be carried out in the analog domain even before the ADC. Table 2 shows the different roles of using FPAAs in an embedded system analog signal path.

Anadigm and Okika are virtually dominant in the market, with prices ranging roughly from \$100 to several hundred USD per chip. A peculiarity is that each device can handle only a few analog channels (4–8 inputs), so implementing 40 channels, as in the previous example, would require multiple ICs. Analog input expansion is also limited when using analog multiplexers – see Fig. 2. Development requires a dedicated software environment, which may be either closed-source or open-source depending on the manufacturer.

Solution	Role of FPAA	Advantage
FPGA + ADC	analog signal filtering, amplification	energy-efficient signal chain
DSP + ADC	analog signal filtering, amplification	energy-efficient signal chain, lower DSP load
MCU + MUX + ADC	analog signal filtering, amplification	energy-efficient signal chain, reduced MCU load
MCU + Comparator + DAC	FPAA as comparator + programmable thresholds	digitally controlled analog trigger logic

Table 2: Roles and advantages of FPAAs in a signal path

C. Multi-core microcontroller architecture

Multicore microcontrollers, such as the Parallax Propeller (priced around \$10–20 per IC or \$40–100 per development board), offer an alternative approach to simultaneous analog signal processing.

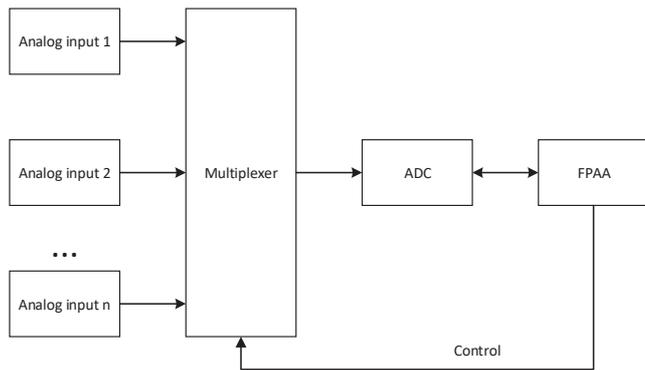


Figure 2: External multiplexer and ADC architecture

Traditionally, analog signal processing operates in a sequential manner: a single microcontroller reads multiple inputs in a time-multiplexed fashion and performs the required computations one after another. This approach is adequate for simple tasks, but as soon as multiple high-frequency or real-time analog signals need to be processed, sequential operation can lead to timing uncertainty, CPU overload, and complex interrupt management.

A multicore architecture addresses this issue at the hardware level. The Propeller microcontroller features eight independent, identical processor cores, all connected through a shared hub memory. Each core can independently handle peripherals, execute programs, and even perform A/D conversion. The deterministic memory access scheme of the hub ensures predictable timing, which is essential for maintaining stability in analog signal processing.

In such an architecture, different signal-processing tasks can be assigned to dedicated cores. For example, one core can perform continuous sampling, while another handles preprocessing operations such as filtering, averaging, or Fourier analysis. A third core may transmit processed data over a serial or wireless interface, while a fourth is responsible for updating display information.

Since each core operates entirely independently, the system can simultaneously monitor and process multiple analog channels in real time without relying on interrupt-driven scheduling or facing timing race conditions. The deterministic timing of this architecture enhances system reliability, which is a critical factor in control and diagnostic applications. Furthermore, programming becomes more straightforward: developers can distribute tasks across truly independent cores instead of managing software-based threads.

Of course, there are limitations. The Propeller 1 (P8X32A) cores are relatively simple, so complex digital signal processing (DSP) operations can only be performed with limited efficiency. In addition, the built-in analog-to-digital conversion relies on software-based methods, which cannot match the resolution or speed of dedicated ADC-equipped hardware. Nevertheless, the flexibility of the multicore design allows the integration of external ADCs, whose data can be processed in parallel by separate cores.

The newer Propeller 2 (P2X8C4M64P) introduces a pipelined architecture capable of handling more advanced 32-bit mathematical operations, further expanding the range of real-time analog signal processing applications. Expanding

the number of ADC input ports also requires the use of external hardware components.

III. SEQUENTIAL SIGNAL PROCESSING ARCHITECTURES

Analog signal processing architectures can be broadly categorized into parallel and sequential (or serial) approaches, each with distinct operational principles and trade-offs. In sequential analog architectures, the signal is processed in a step-by-step manner. Each processing stage completes its operation on the signal before passing it to the next stage. This approach is conceptually simple and requires fewer hardware resources, since only one processing element is active at a time. Sequential architectures are typically implemented using cascaded analog components, such as filters, amplifiers, or modulators, where the output of one stage serves as the input to the next. While these architectures are hardware-efficient and easier to design, they are inherently limited in processing speed, as each operation must wait for the completion of the previous one, and they may accumulate noise and distortion over multiple stages.

D. Microcontroller based architecture with analog multiplexer

A microcontroller has a limited number of analog inputs, and expanding them becomes necessary due to the large number of measurement and control signals. The analog signals to be measured are connected through an analog multiplexer (e.g. CD74HCx4067) to either the pin associated with the microcontroller's analog-to-digital converter or to an external ADC hardware module. For high-speed and high-resolution ADC modules, this provides an effective time-division multiplexing solution.

When multiple external or internal ADC peripherals are used, it is advisable to always measure the same analog signals with the respective ADC modules in order to avoid measurement errors resulting from differences between the converter peripherals. The measurement of short-duration analog signals can be aided by sample-and-hold circuits. It is worth to mention there are ADCs with programmable analog input multiplexers and on-board sample and hold circuitry – for example the MCP3208.

E. Microcontroller based architecture with comparators

To avoid constant polling and data processing, it is recommended to design a system that performs sampling and intervention only when a significant signal change occurs. During the microcontroller's sleep state or instruction execution, it may fail to detect non-nominal variations in the analog signal.

An external hybrid circuit designed as an interrupt request system can continuously monitor the output voltage level and, when a voltage deviation beyond the allowed threshold occurs, issue an interrupt request to the microcontroller. The condition for triggering an interrupt is the deviation of the monitored input from its reference range or connection.

$$INT = \bigvee_{m=1}^n r_{min_n} < a_n < r_{max_n}$$

where a_n is the measured circuit voltage, r_{min} , and r_{max} , are the minimum and maximum threshold values of the monitored circuit voltage, and n is the number of analog inputs.

$$MUX\ output = \sum Analog\ MUX(A_{MUX}, a_n)$$

When the interrupt condition is met, the signal line to be examined further can be selected based on the expression given below.

Fig. 3. illustrates the explanatory operational diagram. Alternatively, a built-in comparator (as part of the microcontroller's internal peripherals) can also be used—especially when the number of analog input signals is low. In this case, the reference voltage value can be set in software as a register value. The internal comparator peripheral can likewise generate an interrupt request to the microcontroller. For external components LMV7219 or MAX9060 can be a solution for the comparator, comparators with on-board DACs are rare, but the MCUs built in DAC periphery or an external DAC IC also can be used (e.g. MCP4728 is a 4 channel DAC with I²C interface). Fore price considerations a reference voltage source and digital potentiometers can be used to generate the comparators reference voltage (e.g. MCP4011, AD5242, MAX5400).

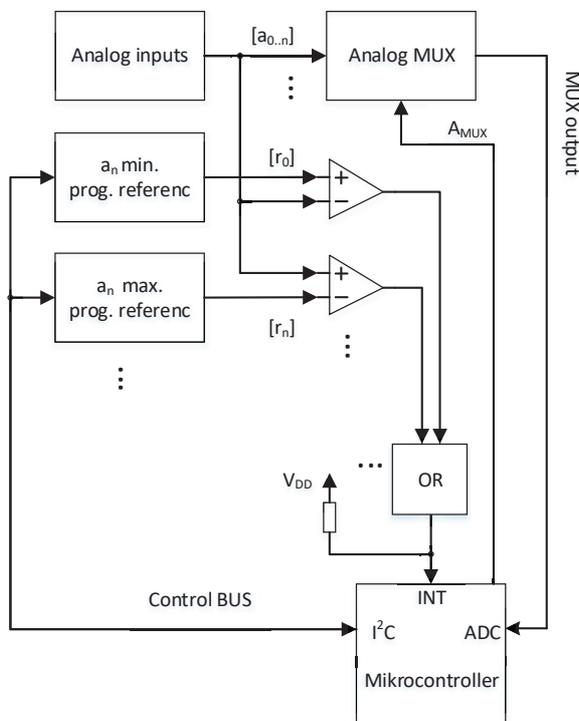


Figure 3: Interrupt base analog reference

The choice between sequential and parallel architectures depends on design priorities. Sequential designs are favored when hardware simplicity, low power consumption, or cost is critical, whereas parallel designs are selected when speed and real-time performance are essential. Table 3 provides a summary overview of the options, features and drawbacks.

CONCLUSION

This study has provided a comprehensive analysis of electronic architectures for simultaneous analog signal processing, including FPGA-, DSP-, FPAA-, microcontroller-based, and hybrid solutions. The comparative evaluation demonstrates that each paradigm exhibits distinct advantages and limitations: FPGAs excel in

high-speed, parallel processing but are constrained by power consumption and area requirements; DSPs offer high-precision, numerically intensive real-time processing suitable for complex filtering, spectral analysis, and adaptive algorithms; FPAAs provide analog-domain configurability with low-latency and energy-efficient operation, though their precision and availability are limited; microcontrollers offer cost-effective, integrated platforms but are restricted in throughput for multi-channel real-time applications; and hybrid analog–digital architectures enable a flexible trade-off among accuracy, speed, and energy efficiency.

Overall, the literature indicates that no single universal solution exists. The optimal choice of architecture depends on the specific requirements of the target application, including bandwidth, latency, signal fidelity, and power constraints. Emerging trends toward hybrid and reconfigurable analog–digital systems suggest that such combinations represent the most promising direction for future developments in parallel, real-time analog signal processing. By leveraging the complementary strengths of analog, digital, and DSP-based domains, these platforms can deliver scalable, efficient, and high-performance solutions tailored to the evolving needs of modern electronic systems.

Aspect	MCU	Multi-core MCU	DSP	FPGA
Simultaneous sampling	no, only with external parallel ADC, typically time multiplexed in SW	limited, with external parallel ADC	yes, with external parallel ADC	yes, with external parallel ADC, very precise
Parallel signal processing	limited (sequential processing)	yes, till the number of processor cores	limited (sequential processing)	yes, full hardware-level parallelism
Floating-point computation	slower, mainly optimized for fixed-point	slower, mainly optimized for fixed-point	fast, dedicated floating-point units	mainly fixed-point, floating-point requires more logic
Development time	short (C/C++, Python)	short (C/C++, Python)	medium (C/C++, MATLAB-generated code)	long (HDL coding, timing closure, simulation)
External ADC required	yes, if nx10 channels need to be synchronized	yes, if nx10 channels need to be synchronized	yes, but integrates well with multi-channel ADCs	yes, capable of handling many channels simultaneously
Sampling rate (for a few kHz per channel)	easily achievable	easily achievable	easily achievable	easily achievable
Deterministic latency	good, but depends on interrupt handling	good, but depends on interrupt handling	good, timing well controllable	excellent, clock-based determinism
Cost (nx10 channels)	very low	low	medium	higher
Power consumption	low	low	medium	higher
Scalability / expandability	limited by available internal hardware peripherals	better, but still limited by available internal hardware peripherals	limited by available internal hardware peripherals	excellent by the reconfigurable logic, modular design
Typical advantage	Low cost, simple development	Low cost, simple development, simultaneous processing in low number of signals	Fast floating-point processing, relatively easy development	Maximum parallelism, precise timing
Typical drawback	Time skew in multiplexed sampling, lower processing performance	Simultaneous processing only in low number of signals	Time skew in multiplexed sampling, more expensive than MCUs	More expensive, longer and complex development

Table 3: Comparison of embedded cogic units based on simultaneous signal processing capabilities

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Electronic Music Effect Generator with FPAA

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Abstract—The timbre of many musical instruments can be modified and coloured with electronic effects. In instruments where the sound produced is essentially sinusoidal or near-sinusoidal, it is common to alter the timbre of these instruments electronically. Two approaches to this are now used; signal modification or frequency domain spectrum modification. Of course, the relationship between the two can be described by Fourier transforms.

Most commonly, effects equipment is used for guitar, electronic guitar. With this article we describe some approaches to this and give recommendations for its implementation with FPAA.

I. INTRODUCTION, VISMAJOR IN THE FREQUENTLY USED METHOD

Most orchestral distortion systems use a comparator (Fig. 1). In this evening, some excess voltage of the sinusoidal signal is squared, producing a 'fundamental' sound with significant harmonic content [1][2]. This is a simple procedure, but setting the right level of comparator is problematic [3][4]. At too low a value, the higher-intensity fundamental harmonic relay is reduced, while at a high comparator reference value, small signal levels are not distorted (Fig. 2, Fig. 3, Fig. 4, Fig. 5). Thus, the "tonality" of the distortion value, the harmonic content of the distorted signal, is highly volume dependent (Fig. 6, Fig. 7, Fig. 8).

In the following, we show some theoretical and practical solutions to overcome this.

II. COMPARISON SIGNAL LEVEL SETTING WITH AVERAGE DEFINITION

Some methods are available for determining the comparator signal level as described above [3][5] [6]. Perhaps the most

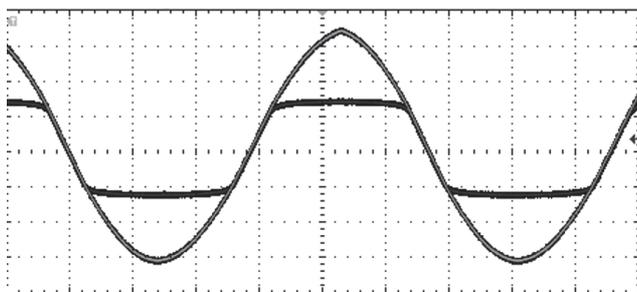


Fig. 1. Sinusoidal signal and distorted signal produced by a parallel diode limiter circuit.

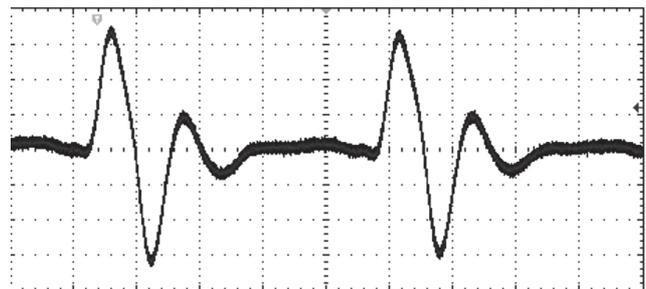


Fig. 2. Time function of two consecutive "E" notes ($\sim 370\text{Hz}$) strummed on guitar

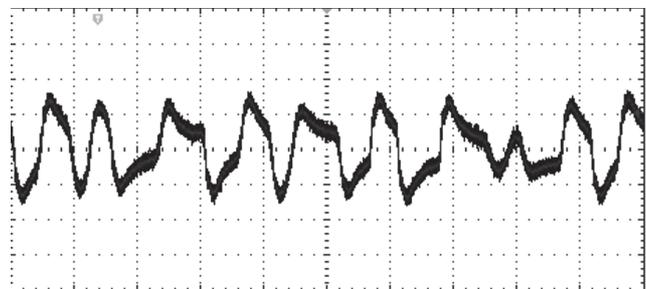


Fig. 3. Time function of the distorted signal of two consecutive "E" notes ($\sim 370\text{Hz}$) strummed on guitar

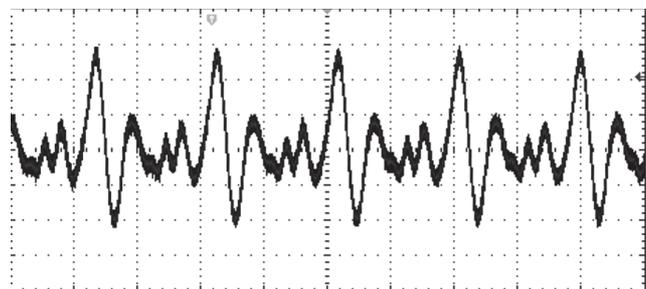


Fig. 4. Continuously strummed "E" sound on guitar..

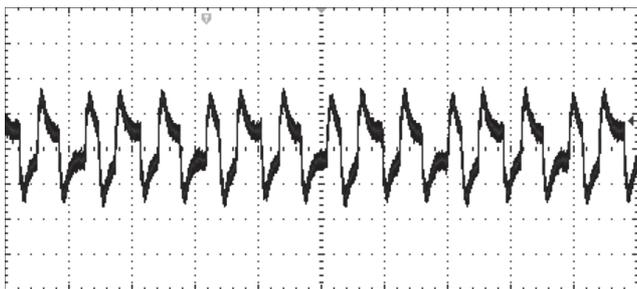


Fig. 5. Distorted sign of the "E" sound continuously strummed on the guitar..

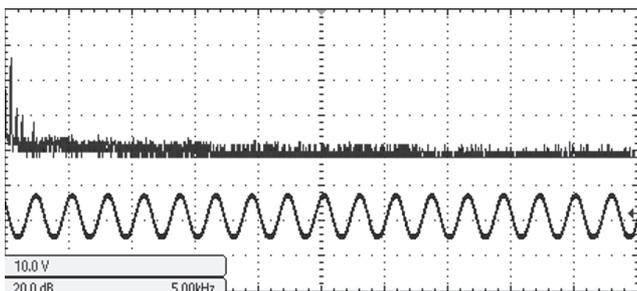


Fig. 6. Normal "a" sound 440Hz near sine wave (bottom) and its spectrum (top).

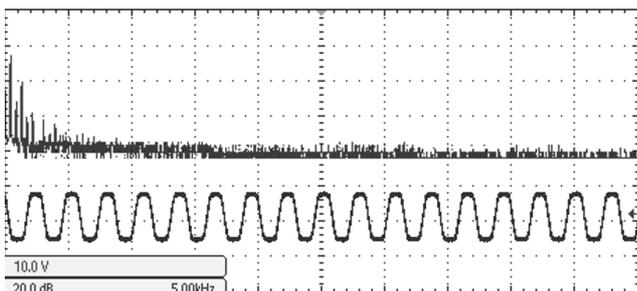


Fig. 7. Normal "a" sound 440Hz distorted sine wave (bottom) and its spectrum (top).

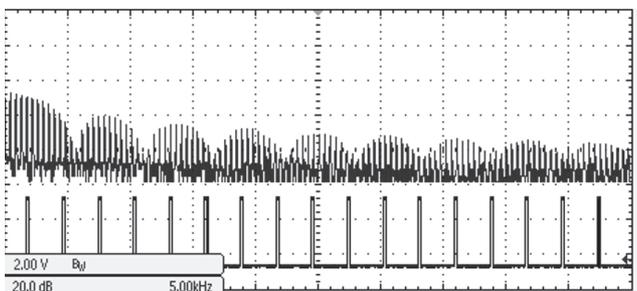


Fig. 8. Normal "a" sound with 440Hz highly distorted signal (bottom) and spectrum (top).

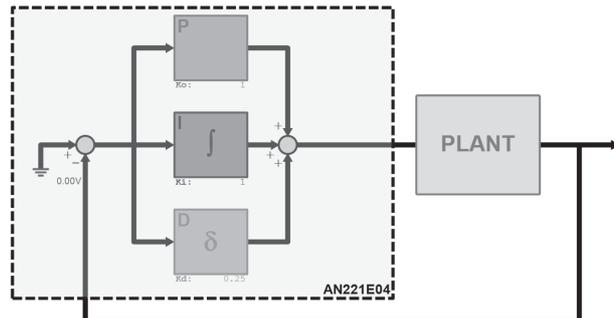


Fig. 9. PID configuration application in the FPAA development environment..

useful is to calculate the average value of the input signal and set the current comparator value as a function of this. This method requires a procedure where the averaging is integrating, proportional and fast enough. The natural answer to this is a PID-type signal conditioning unit (Fig.9) [7][8][9]. The use of the PID algorithm guarantees a sufficiently good averaging, proportional gain/attenuation and a sufficiently fast result [10][11].

III. SOLUTION USING FPAA HYBRID CELL

In previous articles, we have analysed in detail the possibilities offered by FPAA tools, including flexible reconfiguration [12][13][14][15][16][17]. We have also pointed out in these articles that the special relationship between a microcontroller and an FPAA device offers additional possibilities, also as robust electronic circuit solutions. We have referred to this established special connection arrangement as a hybrid controller, or in other contexts as an embedded hybrid controller [18][19][20].

Fig.10 shows the structure of the hybrid cell proposed earlier.

The cell has A_{in} analog and D_{in} digital inputs and A_{out} analog and D_{out} digital outputs [21][22][5][23][24]. The internal topology (n) of the (field) programmable analog

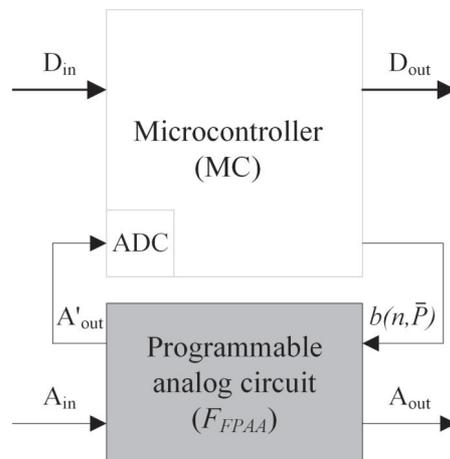


Fig. 10. Interactive connection of microcontroller and FPAA circuit as a hybrid cell.

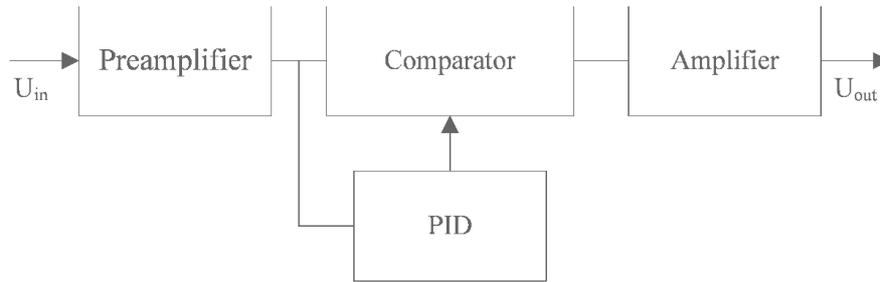


Fig. 11. Block scheme for Distortion, by continuously adjusting the average value of the music signal.

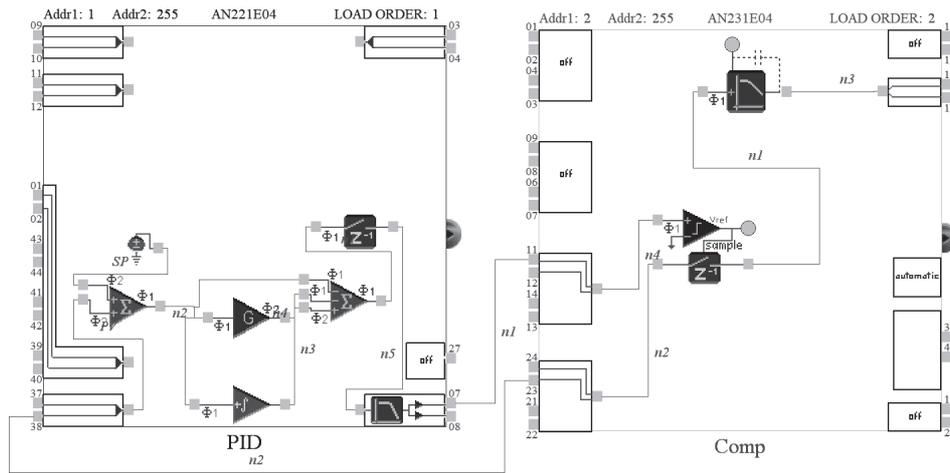


Fig. 12. A bias based on continuous variation of the mean value implemented in two FPAAs. The left circuit contains the PID unit.

array (F_{FPAA}) and the vector of parameters (\bar{P}) of the components are expressed by the microcontroller (MC) as a binary string through the interface $b(n, \bar{P})$ [25][26].

In this case, the connection between A'_{out} and the ADC input of the microcontroller generates the firmware trigger that initiates the reconfiguration.

IV. IMPLEMENTATION OF PID AVERAGING DISTORTION USING FPAA

Fig. 9 also shows that a common application for programmable circuits is the design of a PID circuit. For this purpose, the application (Anadigm) provides a complete design environment, including simulation and the parameterized PID circuit itself, which can be loaded into the FPAA [27][28][29]. In this case, it is also true that the implementation options already influence the design of the architecture at the planning stage. Fig.11 shows a block diagram of the proposed distortion device. The input signal (U_{in}) is fed to a signal level matching amplifier. Its output is the PID averager and the signal trimming comparator. The output of the PID unit continuously adjusts the comparator level as a function of the input signal. The distorted signal is output after a driver amplifier (U_{out}) [30][31][32].

The implementation of the proposed architecture is shown in Fig.12. In the figure, the FPAA on the left (AN221E04)

contains the PID circuit (Figure 9), while the FPAA on the right (AN223E04) contains the comparator and an amplifier that low-pass conditions the output signal. The music signal goes to wire $n2$ (AN221E04₃₈), while the distorted signal is available on wire $n3$ (AN223E04_{17,18}) [33][34][35].

The multifunctionality of the distortion circuit and the wider musical experience offered by the PID parameters depend on the intensity of the input signal, the fundamental harmonics of its frequency. The previously proposed hybrid cell is an excellent choice for arrow-like interactivity [36][37][38].

V. DISTORTION USING A DELAY LINE

We could make a really good quality distortion device if we could use some kind of predictive technique. Of course, this is not possible, because - fortunately - music, the musical signal, is not deterministic.

If the music signal is successfully delayed, we can "predict" the delayed signal from the current (prompt) signal. In live music, this method has very limited application, as the delay affects the musician's habitus. An important criterion, therefore, is to achieve a small delay (Fig. 13). If this is achieved, the comparator cut-off level should be set at or before the maximum (inflection points) of the prompt signal [39][40].

The figure shows a block diagram of the proposed equipment. The U_{in} signal is fed into a preamplifier. Its output is the

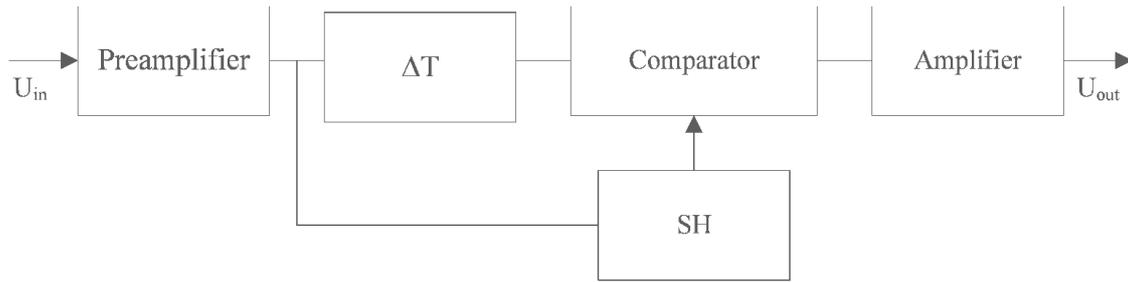


Fig. 13. Block scheme for delay-based "predictive" distortion.

ΔT all-pass "filter" as a delay unit. This of course achieves the minimum possible delay, but still the required greatness. The maximum of the music signal is determined using a sample-and-hold (SH) circuit [41][42]. The maximum search with the sample-and-hold (SH) circuit is a traditional engineering approach; if the value of the sampled signal (u_{SH}) is compared to the value of the current signal (u_t) and u_t is greater than u_{SH} , then we are not yet at the maximum. If $u_t = u_{SH}$, then we have reached the maximum value, i.e. we have reached the inversion point of u_t .

Fig. 14 shows the coupling of a delay line distorter implemented in an FPAA.

VI. CONCLUSIONS

Both of the two methods presented can be implemented in an FPAA circuit. Additional options for implementation include a signal algorithm supported by circuit robustness, and an embedded microcontroller as an operational support method or device.

In the current phase of development, we have focused on possible circuit solutions that can be implemented in FPAA, or further possibilities can be developed with an embedded hybrid controller.

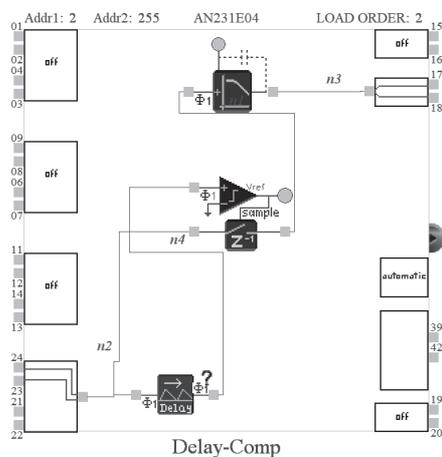


Fig. 14. Theoretical implementation of delay line distortion in FPAA circuit.

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Proving Olympiad Inequalities by Using Some Unusual Ideas

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Abstract— There are a lot of challenging problems concerning inequalities in mathematical olympiads which have an elegant or unorthodox elementary solution. In this paper we will present some of these.

I. INTRODUCTION

In this paper we will prove six olympiad level inequalities using some unusual techniques. Every proof will be completely elementary.

II. THE PROBLEMS AND THEIR SOLUTIONS

First we will prove an inequality, which was proposed in 2010 by the author in the Hungarian competition NMMV.

Inequality 1: Let n be a positive integer number, and let c be a positive constant. If the nonnegative numbers

x_1, x_2, \dots, x_n satisfy the condition

$\sum_{i=1}^n (x_i^2 + ix_i) = c$, then the inequality

$$\sqrt{c + \frac{n^2}{4} - \frac{n}{2}} \leq \sum_{i=1}^n x_i \text{ holds.}$$

Proof:

The most important question is how we can use the condition that the numbers are nonnegative. After some experimentation we can come up with the (maybe surprising) idea that the nonnegativity of the given numbers implies the inequality

$$\sum_{i=1}^n (x_i^2 + ix_i) \leq (\sum_{i=1}^n x_i)^2 + n \cdot \sum_{i=1}^n x_i.$$

This is comfortable for us because the right hand side of the inequality is a second degree polynomial of $(\sum_{i=1}^n x_i)$. Let us denote $\sum_{i=1}^n x_i$ by $\sum_{i=1}^n x_i = z$. Using this notation we have to check for which values of z we have

$$c \leq z^2 + n \cdot z.$$

This inequality is equivalent to

$$0 \leq z^2 + n \cdot z - c.$$

The roots of the polynomial $p(z) = z^2 + n \cdot z - c$ are

$$\frac{-n + \sqrt{n^2 + 4c}}{2} = \sqrt{c + \frac{n^2}{4}} - \frac{n}{2}$$

$$\text{and } \frac{-n - \sqrt{n^2 + 4c}}{2} = -\sqrt{c + \frac{n^2}{4}} - \frac{n}{2}.$$

Thus $p(z) = z^2 + n \cdot z - c =$

$$= \left[z - \left(\sqrt{c + \frac{n^2}{4}} - \frac{n}{2} \right) \right] \cdot \left[z - \left(-\sqrt{c + \frac{n^2}{4}} - \frac{n}{2} \right) \right]$$

Here the factor $\left[z - \left(-\sqrt{c + \frac{n^2}{4}} - \frac{n}{2} \right) \right]$ must be nonnegative, because the value of $z = \sum_{i=1}^n x_i$ is nonnegative.

Thus $\left[z - \left(\sqrt{c + \frac{n^2}{4}} - \frac{n}{2} \right) \right]$ must be nonnegative as well which implies the desired result. ■

Our second inequality is also a problem which was invented by the author and it was posed in the Hungarian competition OKTV in 2012.

Inequality 2: Let $1 \leq k \leq n$ be integer numbers, and let

x_1, x_2, \dots, x_n be nonnegative numbers with sum

$$\sum_{i=1}^n x_i = 1.$$

With these conditions the maximal possible value of

$$x_1 x_2 \cdot \dots \cdot x_k + x_2 x_3 \cdot \dots \cdot x_{k+1} + \dots + x_{n-k+1} x_{n-k+2} \cdot \dots \cdot x_n$$

is $\frac{1}{k^k}$.

Proof:

Here we will use a similar technique to the one we have seen in the solution of the first problem, namely we will smuggle some terms into the expression to be able to tackle the problem more easily.

If we consider the expression

$$x_1 x_2 \cdot \dots \cdot x_k + x_2 x_3 \cdot \dots \cdot x_{k+1} + \dots + x_{n-k+1} x_{n-k+2} \cdot \dots \cdot x_n,$$

then we can note that in every term the k indices cover all possible remainders if we divide them by k . This observation can us inspire to introduce the following partial sums: for every $0 \leq r \leq k-1$, let S_r be the sum of the numbers x_i for which the index i has the remainder r if we divide it by k .

Using this notation we have

$$\sum_{i=1}^n x_i = \sum_{r=0}^{k-1} S_r = 1, \text{ and}$$

$$x_1 x_2 \cdot \dots \cdot x_k + x_2 x_3 \cdot \dots \cdot x_{k+1} + \dots + x_{n-k+1} x_{n-k+2} \cdot \dots \cdot x_n \leq \prod_{r=0}^{k-1} S_r.$$

Using the well known inequality between the arithmetic and geometric means we conclude that the value $\prod_{r=0}^{k-1} S_r$ will be maximal if $S_0 = S_1 = \dots = S_{k-1} = \frac{1}{k}$, thus the value of $x_1 x_2 \cdot \dots \cdot x_k + x_2 x_3 \cdot \dots \cdot x_{k+1} + \dots + x_{n-k+1} x_{n-k+2} \cdot \dots \cdot x_n$

cannot be greater than $\frac{1}{k^k}$.

The value $\frac{1}{k^k}$ can be achieved for example by choosing $x_1 = x_2 = \dots = x_k = \frac{1}{k}$, and $x_{k+1} = x_{k+2} = \dots = x_n = 0$. ■

Inequality 3 will be a problem of the Hungarian competition OKTV from the year 2013. Here one can come up with a surprising and elegant solution.

Inequality 3:

For real numbers

$a_1 \leq a_2 \leq \dots \leq a_n \leq b_1 \leq b_2 \leq \dots \leq b_n$ we have

$$\left(\sum_{i=1}^n a_i + \sum_{j=1}^n b_j\right)^2 \geq 4n \cdot \sum_{k=1}^n a_k b_k.$$

Proof:

Obviously it is enough to prove the inequality

$$\left(\sum_{i=1}^n a_i + \sum_{j=1}^n b_j\right)^2 - 4n \cdot \sum_{k=1}^n a_k b_k \geq 0.$$

The key observation is that the expression on the left hand side is similar to the discriminant of a quadratic polynomial. Let us namely define the polynomial

$$p(z) = \sum_{k=1}^n (z - a_k) \cdot (z - b_k).$$

It is easy to check that its discriminant is

$$\left(\sum_{i=1}^n a_i + \sum_{j=1}^n b_j\right)^2 - 4n \cdot \sum_{k=1}^n a_k b_k.$$

Due to the arrangement of our numbers, the value of $p(a_n)$ cannot be greater than 0, and the value of $p(b_1)$ cannot be less than 0. Thus the polynomial $p(z)$ has a real root, hence its discriminant is nonnegative, and this gives the desired result. ■

The following problem was also posed in the Hungarian competition OKTV in the year 2008. By using a clever substitution we can give a short and elementary solution.

Inequality 4:

If the sum of the nonnegative real numbers t_1, t_2, t_3 is

$$t_1 + t_2 + t_3 = 2\pi, \text{ then}$$

$$2\cos t_1 + 6\cos t_2 + 3\cos t_3 \geq -7.$$

Proof:

The trick is to interpret the problem geometrically. Let us define the vectors $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3$ in such a way that the angle between \mathbf{v}_1 and \mathbf{v}_2 is t_1 , the angle between \mathbf{v}_2 and \mathbf{v}_3 is t_2 , the angle between \mathbf{v}_3 and \mathbf{v}_1 is t_3 , and the length of \mathbf{v}_1 is 1, the length of \mathbf{v}_2 is 2, the length of \mathbf{v}_3 is 3.

We will use the dot products of these vectors. Obviously

$$\mathbf{v}_1 \mathbf{v}_2 = 2\cos t_1, \mathbf{v}_2 \mathbf{v}_3 = 6\cos t_2, \mathbf{v}_3 \mathbf{v}_1 = 3\cos t_3.$$

Thus we have

$$\begin{aligned} 0 &\leq (\mathbf{v}_1 + \mathbf{v}_2 + \mathbf{v}_3)^2 = \\ &= \mathbf{v}_1^2 + \mathbf{v}_2^2 + \mathbf{v}_3^2 + 2 \cdot (\mathbf{v}_1 \mathbf{v}_2 + \mathbf{v}_2 \mathbf{v}_3 + \mathbf{v}_3 \mathbf{v}_1) = \\ &= 1 + 4 + 9 + 2 \cdot (2\cos t_1 + 6\cos t_2 + 3\cos t_3). \end{aligned}$$

This implies that

$$-7 \leq 2\cos t_1 + 6\cos t_2 + 3\cos t_3.$$

The value (-7) can be achieved by choosing for example

$$t_1 = t_2 = \pi \text{ and } t_3 = 0. \blacksquare$$

Inequality 5 is a problem from the IMO (International Mathematical Olympiad) team selection test held in Hungary from the year 2005. No solution was published for this problem, the following one is the proof of the author.

Inequality 5:

If a, b, c, d are nonnegative real numbers such that

$$a^2 - ab + b^2 = c^2 - cd + d^2, \text{ then } (a+b) \cdot (c+d) \geq 2 \cdot (ab+cd).$$

Proof:

Since a, b, c, d are nonnegative, they can be considered as lengths of some segments.

Consider a triangle with one side of length “ a ”, and another side of length “ b ” with an enclosed angle of 60 degrees. Similarly, consider a triangle with one side of length “ c ”, another side of length “ d ”, with an enclosed angle of 60

degrees. The lengths of the third sides in the two triangles are the same due to the law of cosines.

Therefore, due to the generalized law of sines, the radii of the circumcircles of the two triangles are the same. Let the remaining two angles in the first triangle be $(60^\circ - \varphi)$ and $(60^\circ + \varphi)$, respectively, and in the other one $(60^\circ - \mu)$ and $(60^\circ + \mu)$.

Since the radii of the circumscribed circles are equal, by normalizing the original inequality using the law of sines, we should prove the inequality

$$[\sin(60^\circ - \varphi) + \sin(60^\circ + \varphi)] \cdot [\sin(60^\circ - \mu) + \sin(60^\circ + \mu)] \geq$$

$$\geq 2 \cdot \sin(60^\circ - \varphi) \cdot \sin(60^\circ + \varphi) + 2 \cdot \sin(60^\circ - \mu) \cdot \sin(60^\circ + \mu).$$

By using the well known identities

$$\sin(x - y) + \sin(x + y) = 2\sin x \cdot \cos y \text{ and}$$

$$\cos(x - y) - \cos(x + y) = 2\sin x \cdot \sin y$$

the inequality is equivalent to

$$2 \cdot \sin 60^\circ \cdot \cos \varphi \cdot 2 \cdot \sin 60^\circ \cdot \cos \mu \geq$$

$$\geq \cos(2\varphi) - \cos 120^\circ + \cos(2\mu) - \cos 120^\circ.$$

This is equivalent to

$$3 \cdot \cos \varphi \cdot \cos \mu \geq \cos(2\varphi) + \cos(2\mu) + 1,$$

which can be written as

$$0 \geq 2 \cdot \cos^2(\varphi) + 2 \cdot \cos^2(\mu) - 1 - 3 \cdot \cos \varphi \cdot \cos \mu.$$

Both φ and μ lie between 0° and 60° , thus the values of $\cos \varphi$ and $\cos \mu$ lie both between $\frac{1}{2}$ and 1. Thus for appropriate real numbers v and w we have

$$\cos \varphi = \frac{1}{2} \cdot (1 + \sin v), \quad \cos \mu = \frac{1}{2} \cdot (1 + \sin w).$$

We substitute these ones:

$$2 \cdot \cos^2(\varphi) + 2 \cdot \cos^2(\mu) - 1 - 3 \cdot \cos \varphi \cdot \cos \mu =$$

$$= 2 \cdot \left[\frac{1}{2} \cdot (1 + \sin v) \right]^2 + 2 \cdot \left[\frac{1}{2} \cdot (1 + \sin w) \right]^2 - 1 -$$

$$- 3 \cdot \left[\frac{1}{2} \cdot (1 + \sin v) \right] \cdot \left[\frac{1}{2} \cdot (1 + \sin w) \right] =$$

$$= \frac{1}{2} + \frac{\sin^2(v)}{2} + \sin v + \frac{1}{2} + \frac{\sin^2(w)}{2} + \sin w - 1 - \frac{3}{4} -$$

$$- \frac{3}{4} \cdot \sin v \cdot \sin w - \frac{3}{4} \cdot \sin v - \frac{3}{4} \cdot \sin w =$$

$$= \frac{\sin^2(v)}{2} + \sin v + \frac{\sin^2(w)}{2} + \sin w - \frac{3}{4} - \frac{3}{4} \cdot \sin v \cdot \sin w -$$

$$- \frac{3}{4} \cdot \sin v - \frac{3}{4} \cdot \sin w.$$

Using that $\sin^2(v) \leq \sin v$ and $\sin^2(w) \leq \sin w$ we have the following upper estimate:

$$\frac{\sin^2(v)}{2} + \sin v + \frac{\sin^2(w)}{2} + \sin w - \frac{3}{4} - \frac{3}{4} \cdot \sin v \cdot \sin w -$$

$$- \frac{3}{4} \cdot \sin v - \frac{3}{4} \cdot \sin w \leq$$

$$\leq \frac{\sin v}{2} + \sin v + \frac{\sin w}{2} + \sin w - \frac{3}{4} - \frac{3}{4} \cdot \sin v \cdot \sin w -$$

$$- \frac{3}{4} \cdot \sin v - \frac{3}{4} \cdot \sin w =$$

$$= - \frac{3}{4} - \frac{3}{4} \cdot \sin v \cdot \sin w + \frac{3}{4} \cdot \sin v + \frac{3}{4} \cdot \sin w =$$

$$= \frac{3}{4} \cdot (\sin v - 1) \cdot (1 - \sin w).$$

Here $\sin v - 1 \leq 0$ and $1 - \sin w \geq 0$, thus we proved the statement of the problem. ■

Inequality 6 was published in the journal “Matematika tanítása” in 2011. This is a generalization of a problem posed in the competition USAMO in 1980. Here we present the solution of the author of this paper, which differs from the official one.

Inequality 6:

If r_1, r_2, \dots, r_n are real numbers and $S = \sum_{i=1}^n \sin^2 r_i$, then

$$\sum_{i=1}^n \frac{\sin^2 r_i}{S + \cos^2 r_i} + \prod_{i=1}^n \cos^2 r_i \leq 1.$$

Proof:

For every index $1 \leq i \leq n$, let x_i be $x_i = \sin^2 r_i$. Using this notation we have to prove that

$$\sum_{i=1}^n \frac{x_i}{1 + S - x_i} + \prod_{i=1}^n (1 - x_i) \leq 1.$$

The role of the numbers x_i is symmetrical, thus we can assume that

$$0 \leq x_1 \leq x_2 \leq \dots \leq x_n.$$

Now for every index $1 \leq i \leq n$ we have

$$\frac{x_i}{1 + S - x_i} \leq \frac{x_i}{1 + x_1 + x_2 + \dots + x_{n-1}}.$$

Summing up these inequalities we get

$$\sum_{i=1}^n \frac{x_i}{1 + S - x_i} + \prod_{i=1}^n (1 - x_i) \leq$$

$$\leq \sum_{i=1}^n \frac{x_i}{1 + x_1 + x_2 + \dots + x_{n-1}} + \prod_{i=1}^n (1 - x_i) =$$

$$= 1 - \frac{1-x_n}{1+x_1+x_2+\dots+x_{n-1}} + (1-x_n) \cdot \prod_{i=1}^{n-1} (1-x_i) =$$

$$= 1 - (1-x_n) \cdot \left(\frac{1}{1+x_1+x_2+\dots+x_{n-1}} - \prod_{i=1}^{n-1} (1-x_i) \right).$$

Since $1-x_n \geq 0$, it would be enough to prove that

$$\frac{1}{1+x_1+x_2+\dots+x_{n-1}} - \prod_{i=1}^{n-1} (1-x_i) \geq 0, \text{ which is equivalent to}$$

$$(1+x_1+x_2+\dots+x_{n-1}) \cdot \prod_{i=1}^{n-1} (1-x_i) \leq 1.$$

Due to the nonnegativity of the numbers x_i we have

$$(1+x_1+x_2+\dots+x_{n-1}) \leq \prod_{i=1}^{n-1} (1+x_i).$$

Using this observation we get

$$(1+x_1+x_2+\dots+x_{n-1}) \cdot \prod_{i=1}^{n-1} (1-x_i) \leq$$

$$\leq \prod_{i=1}^{n-1} (1+x_i) \cdot \prod_{i=1}^{n-1} (1-x_i) =$$

$$= \prod_{i=1}^{n-1} (1-x_i^2) \leq \prod_{i=1}^{n-1} 1 = 1,$$

which is the desired result. ■

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Multifunctional power unit concept with hydrostatic drive system.

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Abstract. - Peace and war. Two periods that cyclically replace each other in history. What they have in common is that industry must serve both. Current events, such as the Russian-Ukrainian conflict and the threat of terrorism, require preparedness. In addition, it is necessary to economically and adequately satisfy the constant demands of peacetime. Based on this line of thought, we have created an agricultural power plant concept that can also be manufactured under Hungarian conditions. The primary goal of the project is to develop a hydrostatic drive system concept that will serve such a machine.

Keywords - Concept, Power Plant, Hydrostatics, Drive

I. INTRODUCTION

In response to today's conflicts, NATO has determined that member states must spend at least 5% of their GDP on defense spending, which essentially means purchasing military equipment. Furthermore, the general level of preparedness must increase. [1.]

The main beneficiaries of all this are large, multinational arms companies, while the purchasing countries, at significant national economic costs, merely accumulate dead capital.

One of the goals of the concept being presented is to point out the economic benefits of their own development and how development reduces external dependence. Another goal, which is also economic in nature, is to examine how the power machine created as a result of development meets the needs of other sectors of the national economy.

II. THE CONCEPT

The expectations for the development were defined as follows:

- The development should be as simple a construction as possible, in order to be easy to manufacture and operate.
- The development should be usable by as wide a circle as possible.

- The development should meet the needs of military use.

The user group, although we have tried to define it as precisely as possible, is presented in Figure 1 without claiming to be complete.

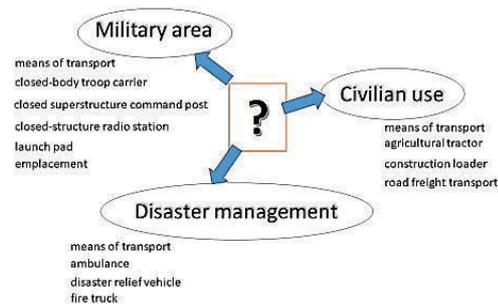


Fig. 1. Areas of application

The concept of a universal tool is not new. There are some very successful tools, such as the Unimog, a product manufactured by Mercedes, which is based on a van. [2]

Our idea differs from these existing tools in two significant points.

- 1). We did not take a truck as the base machine, but an agricultural tractor,
- 2). In order to meet the different needs in different areas of use – typically travel speed – and to ensure easy variability, we chose a hydraulic drive.

There is also practical experience with the hydraulic drive, since the Forscrit E 516 agricultural harvester was already manufactured with such a drive in the 1980s.[3.]

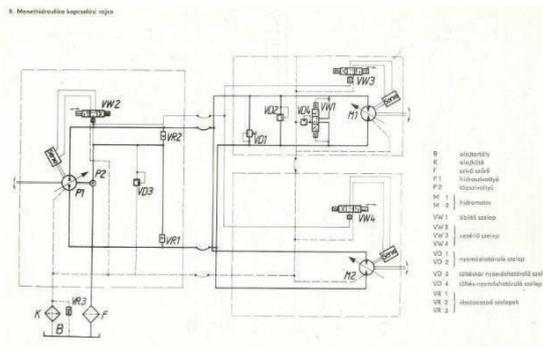


Fig. 2. E-516 combine travel hydraulics system.

Although the schematic diagram of the drive system provides assistance in the design, from the perspective of the concept design, the design of the drive system still represents the greatest challenge, as it must be adapted to the unique needs of different designs.

III. CONCEPT DETAILS

As the basic machine, we chose the form and construction of an agricultural power plant - a tractor - due to its universal nature. Its frame structure is a longitudinal and cross-beam system made of welded U profiles, on which the power unit, the drive train, the 180° rotating operator's cabin and all additional elements can be placed. The frame structure is illustrated in Figure 3, together with the listed elements.

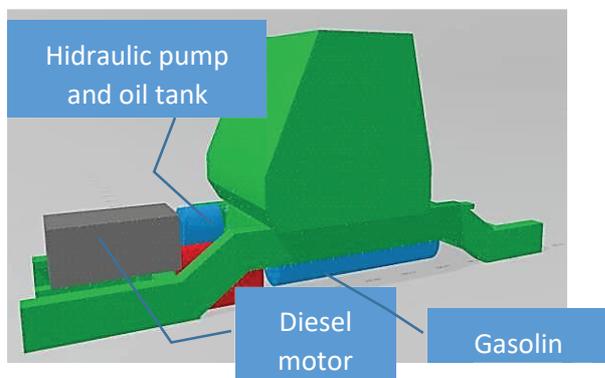


Fig. 3. Frame structure and main structural elements

This basic structure is the same in each variant. Differences occur in the chassis, drive system and bodywork.

Chassis. The chassis is suitable for:

- four wheels,
- two wheels and two tracks, and □ four tracks.

The individual chassis elements can be freely exchanged according to needs, as their drive

systems are compatible. Its construction is shown in Figure 4.



Fig. 4. Track model.

Superstructures. To accommodate superstructures, the basic frame is supplemented with a so-called frame extension. This increases the length of the basic model and makes it suitable for:

- low or medium-height platform, i.e. loading area,
- raised, open platform,
- for receiving closed boxes, - which can be:
 - o troop carrier with rear opening ramp,
 - o command post, o communication center, o chemical protection station,
 - or o even a cold storage room, or
- for using the chassis of the base machine as a platform. Figure 5.



Fig.5: Frame extension

Drive chain. As mentioned earlier, perhaps the most important element of the concept is the hydrostatic drive system, against which the basic requirement is to ensure different travel speeds in different application areas. The system must be able to achieve any value within the speed range of 4 km/h and 100 km/h. Several alternatives for the design of the drive system are included in the concept. In order of complexity, we have to consider the following options:

- 1- A hydraulic motor drive located on a central drive shaft. (two-wheel drive)
Figure 6
- 2- Two central axles with one hydraulic motor per axle (four-wheel drive)
- 3- Wheels driven by two independent hydraulic motors. (two-wheel drive)

- 4- Four independent hydraulic motor driven wheels. (four-wheel drive)

We performed preliminary calculations for all four cases to determine the theoretical functionality of the design and to determine the size and power requirements of the required power source (internal combustion diesel engine).

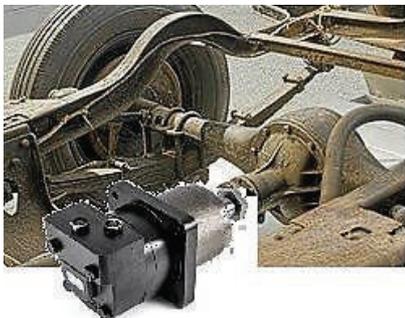


Fig.6: Rigid rear axle, direct hydraulic drive mounted on the differential

In determining the initial data, we relied on the data of the previously mentioned E-516 combine harvester, which, according to the manual: [5.]

$$P_{\max} = (228 \text{ LE}) 168 \text{ [kW]} \quad n = 2200 \text{ [1/min]}$$

$$M_{\max} = 961 \text{ [Nm]} \quad n = 1400 \text{ [1/min]}$$

$$v_{\max} = 20 \text{ [km/h]} \text{ without degree four-wheel drive}$$

$$Q = 196 \text{ [l/min]} \text{ by swallowing liquid } p_{\text{üzemi}} = 350 \text{ [bar]}$$

Based on these data, we chose the Deutz TCD 4.1 L4 Agri type as the power source. Picture number 7 [4.]



Fig. 7: Deutz TCD 4.1 L4 Agri

Characteristic data:

$$P_{\max} = 126 \text{ [kW]} \quad n = 1900 \text{ [1/min]}$$

$$M_{\max} = 699 \text{ [Nm]} \quad n = 1500 \text{ [1/min]}$$

The hydraulic system was optimized and calculated based on these data.

The calculation determined:

- The size and fluid delivery of the hydraulic pump that can be driven by the selected resource, at an operating pressure of 350 bar (The data of the hydraulic pump are presented in Table 1 of the results chapter.)
- Based on the volumetric flow, the fluid intake of 1-2-4 hydraulic motors and from this, the speed and torque of the hydraulic motor.
- The speed and torque that can be transmitted to the driven wheel from the speed and torque of the hydraulic motor, in the case of direct drive and indirect drive.
- The magnitude of the starting torque calculated from the vehicle's mass.

IV. RESULTS

Selected tractor wheel dimensions: 320/85R28

During calculations, we calculated with a vehicle weight of 5 tons.

From these calculated data, a comparative evaluation could be carried out, based on which it could be decided whether a given drive design can meet the expectations and technical parameters of a given purpose of use.

TABLE. I. Operable hydraulic pump data

Típe	Q [l/min]	n [1/min]	p _{max} [bar]
A10VSO s 32	252	1800	350
A20VLOseries10	2x230	2700	350



Fig. 8: A10VSO series 32 140 [7]



Fig. 9: A20VLO Series 10 [7]

The evaluation and summary data of the drive design methods are contained in Table 2.

TABLE. II. Summary review

	1 hm. thq.	2 hm. thq.	2 hm. direkt	4 hm. direkt
Th/rot	200	2x200	2x200	4x200
Rev/rot	2000	2000	2000	317
Rev	426	425	200	317
Speed	100	50 (leszabál yozva)	50	75
Usage.	Truck	Tractor	Half caterpillar	Full track

Legend:

- 1 hm. thq. – 1 hydraulic motor placed on a central shaft.
 2 hm. thq. – 2 driven central shafts, driven by 1-1 hydraulic motor. 2 hm. direkt – 1 – 1 hydraulic motor placed on wheels, either on the front or rear wheel pair.
 4 hm. direct – four-wheel drive with 1 – 1 hydraulic motor on each wheel.
 Th/rot – torque per motor available in the drive [Nm]
 Rev/rot – speed of the hydraulic motor/s used in the drive [1/min]
 Rev – Wheel/track speed [1/min]
 Speed – maximum travel speed achievable with the vehicle [km/h] Usage – Possible area of application of the drive.



Fig. 10: A10 VER Series 52 45 Motor [8]

V. FINDINGS

In the case of a solution mounted on a 1 hm central shaft, the single pump and 4.7/1 differential ratio are used, and the design is capable of a maximum speed of 100 km/h.

2 hm. in a solution mounted on a central axle, with the double pump it is able to maintain the speed of the single-axle solution, i.e. 100 km/h. In addition, it can be suitable for receiving 4x4 wheels or caterpillar tracks, thus fulfilling an off-road vehicle function. Remaining at a total weight of 5 tons, regulated to max. 50 km/h

2 hm direct drive in the case of semi-tracked reduced to 50 km/h the configuration may be suitable for a semi-tracked solution

With 4hm direct drive, the double pump is the most suitable, even driving 4 motors does not limit the system. In this case, the maximum speed achieved is 75 km/h.

The calculated data supported the basic conceptual idea that a vehicle structure that can meet universal requirements can be created with a hydraulic drive

system. The correctness of the concept is also supported by similar research by Chinese experts. [6.]

In the theoretical system, dual regulation can be implemented, which on the one hand means regulating the charge level of the driving diesel engine. This allows the speed of the central hydraulic pump, and thus the amount of fluid flow available, to be regulated.

- A second control circuit can be implemented on the application side, by throttling the hydraulic motors, which relates to the pressure and/or amount of fluid flow.

In continuing to develop the concept, we still need to do:

- specific weight calculations for the basic machine and the superstructures assigned to different areas of use,
- sizing of additional hydraulic systems (e.g. PTO drive, 3-point suspension, loading boom, or propeller drive.)
- buoyancy calculations,
- design plans
- cost calculations.

We hope that this will create a development direction that will help domestic vehicle manufacturing.

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An information and analytical system for optimizing the security of educational institutions

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Abstract—The research focuses on the analysis of system components and their interaction efficiency. The study examines the architecture of integrated security systems, including access control, video surveillance, and emergency response mechanisms. The block diagram demonstrates the interconnection of critical system elements. The findings highlight the significant role of information security solutions in enhancing educational facilities protection.

Keywords—data, system, schools, universities, secure

I. INTRODUCTION

In the current landscape of increasing threats, both physical and digital, keeping educational institutions secure is a top issue. Schools and universities seek to make safe spaces, but standard safety methods may not be flexible enough to handle new dangers. Because of this, there is a need for complete solutions that use real-time data analysis with forward-thinking choices. This paper puts forward an information and analysis system to make educational security better. The study starts by looking at how secure institutions currently are, noting problems like broken-up infrastructure and not enough ways to respond to threats. Based on this, the research shows a system setup that brings together data processing, risk evaluation, and connection with current safety tools. A main new part is its feedback-based way, which allows constant change to new threats.

II. THEORETICAL FOUNDATIONS AND PROBLEM STATEMENT

Educational institutions today face intertwined physical and cyber risks. Although many universities use surveillance (84%), less than a third (32%) link it to their cyber defenses. This creates security gaps [1]. Laws like FERPA and GDPR require data protection, but many schools and universities still have issues. Around 68% of U.S. schools can't monitor access logs and network activity from one place, which leaves them open to attack [2].

This trend is exacerbated by the fact that ransomware attacks on schools rose by 84% in 2023, often targeting research and student data [3]. Physical security issues, like unmonitored entrances, also add to the danger by allowing unauthorized access. Campus intrusions may happen due to outdated access controls, especially when school is out of session, but this requires further study.

More IoT devices in classrooms also create risks since unsecured devices can be gateways for attacks. These challenges demonstrate the limitations of traditional security methods that operate in silos. For example, CCTV systems usually don't connect to intrusion software, which slows down responses to coordinated attacks.

A possible solution is using predictive analytics to link data from different sources, like network logs and motion sensors. A combined system could spot unusual activity, like cyber intrusions and physical breaches happening at the same time, which could speed up response times.

However, this approach requires testing its effectiveness, especially with legacy systems. The growing threat landscape necessitates rapid changes because current reactive security measures cannot keep up with emerging dangers. This situation calls for a fundamental reevaluation of how we secure educational institutions.

When conducting a qualitative risk assessment, the primary concern is the chance of something happening, not its precise statistical likelihood. This chance is determined by examining potential threats and weaknesses, and then assigning a descriptive or numerical rating to the value of the asset(s) that could be impacted [4]:

$$Risk = T \times V \times I \quad (1)$$

where T – Threat, V – Vulnerability, I – Impact (Threat × Vulnerability is likelihood).

One example of qualitative risk rating methodology is the OWASP (Open Web Application Security Project) Risk Rating Methodology [5]. After OWASP completes its assessment, it produces a summary report. This report is structured similarly to the example in Figure 1. The report uses qualitative ratings – Low, Medium, or High – to describe the Impact and Likelihood of the identified issues.

Overall Risk Severity				
	HIGH	Medium	High	Critical
Likelihood	MEDIUM	Low	Medium	High
	LOW	Note	Low	Medium
		LOW	MEDIUM	HIGH
		Impact		

Fig. 1. OWASP Risk Rating Methodology

III. SYSTEM ARCHITECTURE AND FUNCTIONAL COMPONENTS

Today's schools and institutions need all-in-one systems that address both physical and cyber safety. The system described here uses a mixed setup where IoT devices like cameras and RFID readers send data through MQTT gateways. This configuration is expected to cut down on data transmission delays by 20-25% compared to older methods [6]. However, schools and universities with older tech may have to spend a lot to update their networks.

For analyzing data, Kubernetes clusters in a cloud setup handle data streams in real time, which allows for growth when needed. Federated learning is used to train the models, letting schools and universities work together to improve algorithms without sharing private data. This method is designed to meet regulations and lower the chance of leaks by 30–40%, but further evaluation is required to assess its long-term effectiveness. The data storage is on a blockchain, where each point only sees encrypted log hashes. Early tests in schools and universities show that this setup cuts down on audit times by about 25%. Nevertheless, the complex configuration could pose challenges for smaller schools and universities.

The way data is handled combines Isolation Forest algorithms to spot unusual network traffic and graph neural networks (GNNs) to analyze the links between physical and cyber events. If someone tries to access a server many times and also enters a building without permission, the system will respond. This integrated approach is projected to make detection 15–20% more accurate, though it will also require more computing power. Event handling through Apache Flink keeps delays under 100 ms, even with a lot of events happening at once (800,000 events/sec). However, when tested in a situation that simulated a large campus (5,000+ sensors), delays went up to 180 ms [7]. These results indicate that the algorithms need optimization for high-load scenarios.

To lower the number of false alarms, dynamic threshold adaptation is used. A Transformer-based neural network analyzes the context of incidents and automatically adjusts detector sensitivity. This implementation is anticipated to reduce false alarms by 35–40%, though it will necessitate quarterly model updates, thereby increasing costs.

In summary, the system’s capabilities demonstrate potential in combating hybrid threats. However, implementation presents technical and financial challenges, particularly for resource-constrained schools and universities. The system’s design allows compatibility with existing security systems, such as SIEMs, which helps reduce initial costs by repurposing older equipment. Nevertheless, this flexibility can introduce certain complications. Some systems require special adapters, which prolong deployment times and increase dependency on suppliers for support.

To monitor both digital and physical security simultaneously, the system utilizes standard APIs to share real-time data between access control systems and network sensors. This integration enhances situational awareness, though vulnerabilities in external integrations could create security weaknesses, which is particularly concerning for educational institutions handling sensitive research data.

These combined data streams feed into active risk assessment algorithms that prioritize threats by evaluating asset value, anomalous behavior, and historical incident patterns. For example, if someone repeatedly attempts to access a student database and subsequently enters a lab after hours without authorization, the alert level increases. This contextual analysis is intended to accelerate responses to coordinated attacks but may result in overly strict risk models missing novel threats, such as deepfake-based intrusions. These limitations highlight the necessity for regular model updates, especially as educational institutions integrate IoT devices and cloud-based tools where traditional threat indicators may no longer be effective.

Scalability also tests the system’s viability. While federated learning enables schools and universities to collaborate on model training, smaller institutions often lack the resources to maintain blockchain nodes or process real-time analytics. Conversely, large universities benefit from distributed architectures when monitoring multiple campuses, but unreliable networks in remote locations could delay threat mitigation, undermining the system’s real-time response capabilities. This disparity exacerbates the existing resource gap between well-funded and under-resourced educational institutions.

IV. PRACTICAL IMPLEMENTATION AND EVALUATION

A hybrid security system (Fig. 2) starts with designing a complete incident management plan. Data from cameras, RFID readers, and network sensors goes into a single system. Then, algorithms spot unusual activity as it happens [8].

These signals go to a risk assessment part of the system. This part considers how important the asset is and what the threat is. The system then either stops the suspicious activity or sends an alarm by working with SIEM platforms. Old access control systems can cause slowdowns, as even small data delays can hurt how well the system predicts problems. This issue necessitates extra steps to sync data.

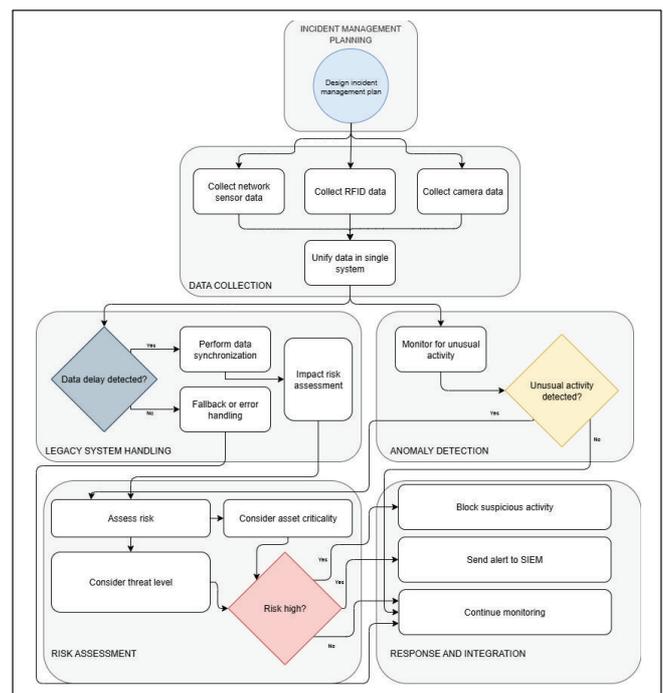


Fig. 2. Hybrid Security System Flow Chart

Putting the system in place means balancing new ideas with what is already there. After checking for weak spots in physical and computer security, a test launch happens in limited areas. A simulated attack on cloud storage and physical infrastructure can show how the system handles combined threats. A lot of resources go to adapting old equipment, like connecting analog cameras to new audit logs. The system is expanded to the whole campus only after fixing how all the parts work together. Staff also get training to use a single interface.

The system’s performance is checked using key numbers: the rate of false alarms (the goal is 5%), how fast the system responds to incidents (up to 45 seconds for computer attacks), and how well it resists known threats (95% successful stops). Early detection of unusual activity, such as stopping phishing attempts, could reduce the number of incidents approximately by 30%. Hidden costs, like keeping up distributed nodes, may be too high for organizations with small budgets, especially if they don’t have good IT support [9].

Whether it pays off depends on the size of the threats and how flexible the system is. Avoiding data leaks, lowering the risk of penalties, and automating regular tasks can make up for the initial cost of 12-15 million rubles for a typical university. Small organizations, including regional schools and universities, need to adapt the system to their needs, such as using simpler solutions instead of resource-intensive parts, without losing key features. This can maintain up to 80% efficiency while cutting costs, which matters a lot for institutions with limited budgets.

V. CASE STUDY

Integrating adaptive security architectures in education calls for clear risk assessment to back up spending and guide protection plans [10]. This study uses the OWASP Risk Rating method to check a typical weakness in school systems before and after adding a mixed security setup. By comparing risk scores in tech, operations, and reputation, the study shows that modern security setups can change risk profiles and stay budget-friendly for educational institutions of all sizes.

- Pre-Implementation Scenario

A school’s electronic gradebook system with SQL injection vulnerability in student data access module:

TABLE I. PRE-IMPLEMENTATION PROBABILITY

Risk Factor	Score	Rationale
Attacker skill level	6/9	Basic database exploitation knowledge
Vulnerability detectability	7/9	Identifiable via SQL query testing
Exploitation complexity	8/9	Standard UNION-based attack
Automation potential	+2	SQLMap-compatible
Detection capabilities	5/9	Intermittent log monitoring

TABLE II. PRE-IMPLEMENTATION IMPACT

Impact Dimension	Score	Consequences
Availability loss	6/9	2–4 hours of unauthorized data access
Accountability breach	8/9	Grade manipulation potential
Reputational damage	9/9	Law violation penalties
Technical severity	7/9	Full DB compromise

Total Pre-Implementation Risk: $5.6 \times 7.5 = 42$ (Critical)

The pre-implementation risk assessment reveals a critical security posture with a total risk score of 42, indicating an urgent need for comprehensive security enhancements.

- Post-Implementation Scenario

The same electronic gradebook system, now safeguarded by a hybrid security framework, demonstrates radically transformed risk parameters:

TABLE III. POST-IMPLEMENTATION PROBABILITY

Risk Factor	Score	Rationale
Attacker skill level	5/9	System blocks 89% of advanced attacks
Vulnerability detectability	3/9	Behavioral analysis masks vulnerabilities
Exploitation complexity	4/9	Multi-factor authentication layer
Automation potential	+1	Limited by heuristic filters
Detection capabilities	9/9	Real-time anomaly detection

TABLE IV. POST-IMPLEMENTATION IMPACT

Impact Dimension	Score	Controls
Availability loss	3/9	Backup restoration
Accountability breach	5/9	Blockchain audit trails
Reputational damage	5/9	Incident response <1 hour
Technical severity	4/9	Isolated data containers

Total Risk: $4.4 \times 4.25 = 18.7$ (Medium)

This risk reduction demonstrates how adaptive security architectures fundamentally alter risk profiles. The system’s components decreased exploitation likelihood by 21.4%, while recovery mechanisms limited potential damage severity by 43.3%.

VI. CONCLUSION

A hybrid security system could change how university campuses are kept safe by mixing prediction with adaptable reactions. System must use sensors, find unusual activity, and automatically stop threats. The system's success relies on how well it can adjust and whether it considers the limited resources of schools. Large universities that have strong computer systems may get their investment back in 2-3 years.

The system's future growth depends on it being able to change as threats quickly change. The next steps could be to use machine learning to study behavior, connect with country-wide cybersecurity systems, and create standard rules for older equipment. Right now, the model acts as a base for making security plans. It proves that keeping campuses safe means building systems where different protections work together.

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Implementing an Audio Compressor Effect with AGC on a Microcontroller

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Abstract- This paper presents the design and implementation of an audio compressor effect based on the Automatic Gain Control method using a microcontroller platform. The proposed system continuously monitors the input signal amplitude and dynamically adjusts the gain to maintain a consistent output level, thereby reducing distortion and enhancing audio clarity. The architecture combines analog front-end circuitry with digital signal processing executed on the microcontroller, ensuring low latency and efficient resource utilization. Experimental results demonstrate that the developed prototype effectively suppresses sudden volume fluctuations while preserving the natural quality of the audio signal. The solution provides a cost-effective and compact alternative to traditional compressor units, making it suitable for portable audio devices, embedded systems, and educational applications.

Keywords - Audio Compressor, Automatic Gain Control, Microcontroller, Embedded Systems, Audio Signal Processing, Real-Time Processing, Low-Cost Implementation

I. INTRODUCTION

The conversion of raw audio signals from electric instruments is an essential step in producing a usable output [1]. With the advent of digital audio effects [2], several methods have been developed to digitally model and manipulate analog audio signals [3]. The compressor effect controls the volume fluctuations of the input audio signal using various parameters [4, 5]. In the proposed implementation, the base signal is duplicated: one copy remains in analog form, while the other is fed into a microcontroller. After evaluation, the microcontroller generates a corresponding control signal that regulates the duplicated analog signal path [6].

II. THEORETICAL BACKGROUND

When using the compressor effect, amplitude regulation is performed. This process is known as Automatic Gain Control (AGC) [7]. A threshold voltage level is set with a potentiometer. If the input signal exceeds this threshold, the Arduino initiates amplitude regulation, adjusting the signal strength back to the threshold level. The ramp-up and ramp-down characteristics of the control can be manually adjusted using the potentiometer corresponding to the attack parameter. The input signal is fed to a potentiometer, and by applying a sine wave as the input, the amplitude can be easily varied, allowing direct observation of the control circuit's behavior [8].

A. Analog circuitry

The unity-gain preamplifier stage (see at Fig. 1.) ensures impedance matching. A low-impedance input signal must be applied to the Arduino Uno analog input to ensure that the sampling capacitor charges correctly and provides accurate sampling. This circuit reduces the high input impedance to approximately $100\ \Omega$, ensuring proper operation of the Arduino sampling capacitor. The DC component of the input sine signal is removed with a coupling capacitor, yielding a pure AC waveform. This signal is then shifted to 2.5 V DC using a KF-25 DC-DC converter IC, aligning the average signal level with the midpoint of the microcontrollers 0–5 V input range – follow at Fig. 2.

The microcontroller used is an Arduino Uno, employed exclusively for control. Regulation is carried out by an MCP41100 digital potentiometer. The control signal from the Arduino is applied to the digital potentiometer, which adjusts the amplitude of the analog signal using the principle of voltage division (follow at Fig. 3.). The output signal of the potentiometer is then fed into the output amplifier circuit, which is based on a bipolar junction transistor. This stage is identical to the Electro-Harmonix LPB-1 booster circuit [9]. Unlike the emitter-follower configuration used for preamplification, the common-emitter amplifier employed here provides high voltage amplification [10]. The amplitude of the final output signal can be adjusted using a potentiometer, which functions as the volume control [11, 12].

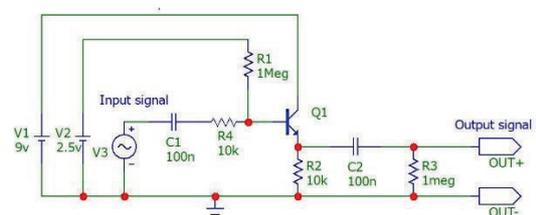


Figure 1: Unity gain schematic

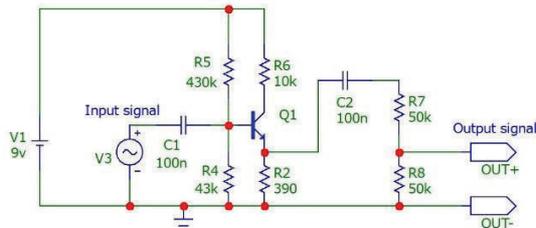


Figure 2: LPB-1 booster schematic

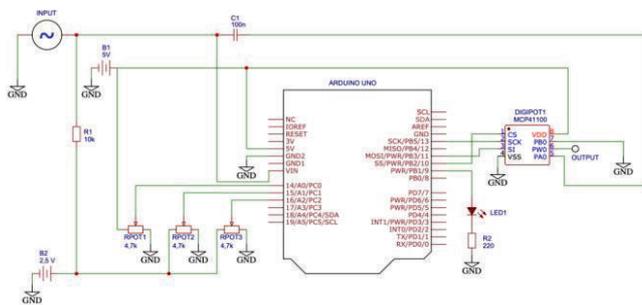


Figure 3: Integration of Arduino Uno into the analog circuit

B. Software realisation

SPI communication is used for data transfer. SPI is a master-slave serial communication protocol that allows for high-speed communication [13]. In this implementation, SPI is employed to control the outputs. Pin 10 is configured as an output; its initial state is set high to disable the SPI command, since the protocol is active low. The SPI bus is then started and the serial port initialized [14].

The control pin for the MCP41100 digital potentiometer is declared. The potentiometer is connected through output pin 10, which delivers the control signal. An indicator LED is also defined, connected to output pin 9. The LED provides visual feedback of the regulation process: its brightness is directly proportional to the control signal. The LED is connected to ground through a 220 Ω resistor, ensuring a current of approximately 9 mA, which is within the safe operating range of the component.

The analog inputs are defined as follows: the base signal is fed to port A0, the threshold potentiometer to port A1, and the attack potentiometer to port A2. An Exponential Moving Average (EMA) algorithm is implemented to determine the ramp-up and ramp-down characteristics of the control [15]. The resulting envelope signal is compared against the threshold to specify the required degree of regulation. Instead of a true moving average, the algorithm computes a decaying envelope that follows the signal peaks [16]. Ramp-up and ramp-down are handled separately, improving robustness against sudden dynamic changes [17].

The variable "emaPeak" is computed as the sum of two weighted terms: the current sample multiplied by a weighting factor, and the previous average multiplied by the complementary factor [18-20]. The weighting factor, adjustable with the A2 potentiometer, controls how strongly the most recent sample influences the peak value. When the algorithm detects a decreasing voltage, its sensitivity is reduced by a precalculated factor, based on empirical data, by applying a scaled version of the attack parameter, thereby smoothing the release phase [20-23].

The main program acquires the signals connected to the analog input pins and scales them into voltage values. The Arduino performs analog-to-digital conversion with 10-bit resolution, corresponding to a scale of 1024 discrete units. A voltage of 0 V is represented as 0, while 5 V corresponds to 1023. To convert the digital values back to voltage, each signal is divided by 1023 and multiplied by the upper limit of the desired scale. In this implementation, the input signal is scaled to 5 V, while the potentiometer values are scaled to 2.5 V. Scaling to 2.5 V is appropriate for the threshold parameter because the input signal is offset to 2.5 V, giving it a theoretical AC range of ± 2.5 V. Considering that a highly dynamic guitar signal typically has an amplitude of about 0.5 V, this range provides a suitable reference.

The attack parameter is scaled independently, and its absolute voltage range is less relevant. For consistency in graphical representation, both control potentiometers are scaled to a maximum of 2.5 V, which facilitates direct comparison of their positions. In addition, the attack potentiometer is normalized to a range between 0.01 and 1, enabling its direct use as a weighting factor in the EMA algorithm. The previously mentioned attack/release ratio is also evident in this part of the program.

In the subsequent stage, the amplitude of the input is calculated by removing the nominal 2.5 V offset, effectively centering the waveform around 0 V. This adjusted signal is used to determine the voltage of the envelope curve, which is compared against the threshold to evaluate whether regulation is required. If the EMA voltage exceeds the threshold, a control signal is generated with a magnitude proportional to the difference between the two values. The control output is then converted to 8-bit resolution, yielding a scale of 0-255 for driving the potentiometer and the LED. At this stage, the scaling of the output signals is also performed. The LED is controlled via a PWM signal, while the digital potentiometer operates through a resistance ratio applied between pins 5 and 6, thereby realizing voltage division of the base signal.

Finally, the relevant signals – including the input signal, threshold level, envelope average, and attack level – are displayed graphically. The flowchart of the software can be followed at Fig. 4.

III. PRACTICAL REALISATION

During testing, the threshold was set to 0.5 V, monitored via the Arduino IDE graphical interface. The objective was to observe and document the signal waveforms at various measurement points as the input amplitude varied. The expectation was that once the input exceeded the threshold, both the regulated base signal and the amplified signal from the LPB-1 would remain at a constant level.

Measurements were performed using an XR2206 function generator and a Siglent SDS 1104X-E oscilloscope. Three probes monitored the input, regulated, and amplified signals, each at a resolution of 500 mV per division. In addition to the oscilloscope readings, changes in the LED brightness provided a qualitative indicator of regulation. The results confirmed expectations: as the input amplitude increased beyond the threshold, the regulated and amplified signals stabilized at a fixed level, while their waveform shape remained unchanged. The experimental environment and the

measurements of the developed system can be followed in Fig. 5. to Fig. 8.

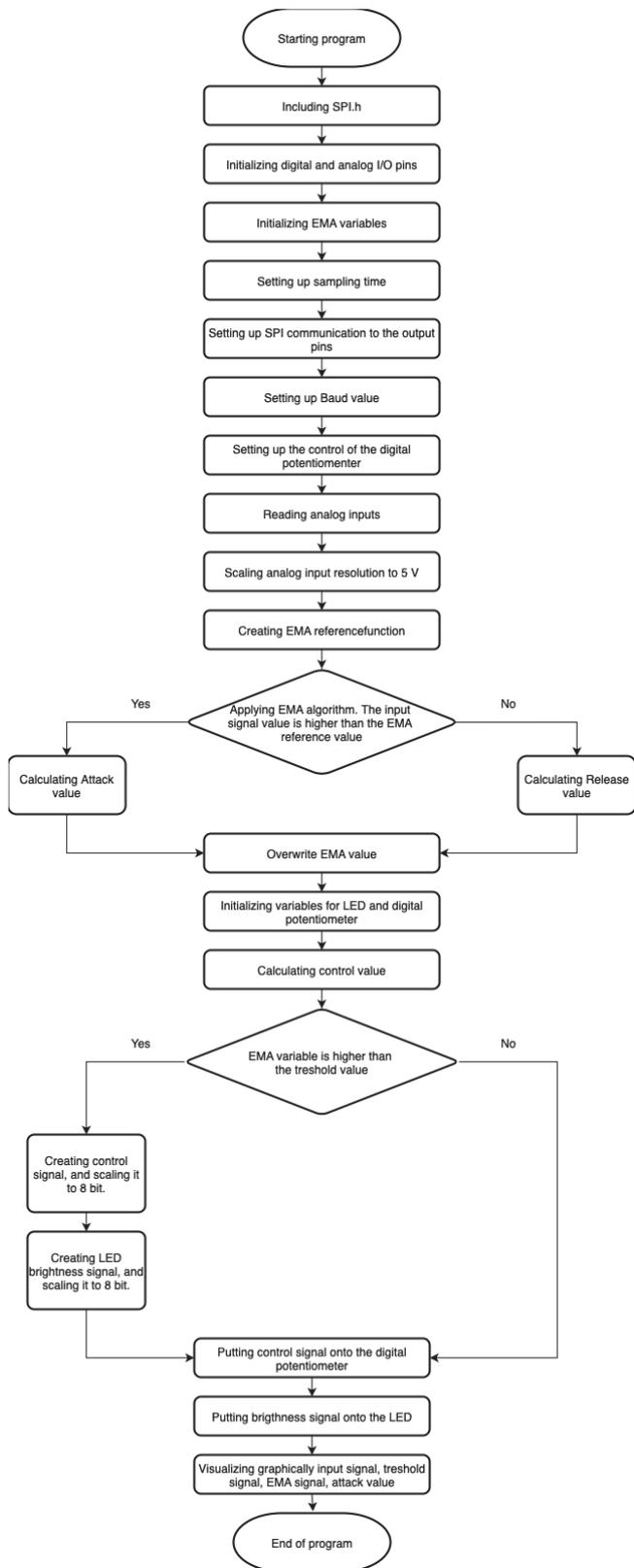


Figure 4: Program flowchart



Figure 5: Input signal level is lower than threshold level

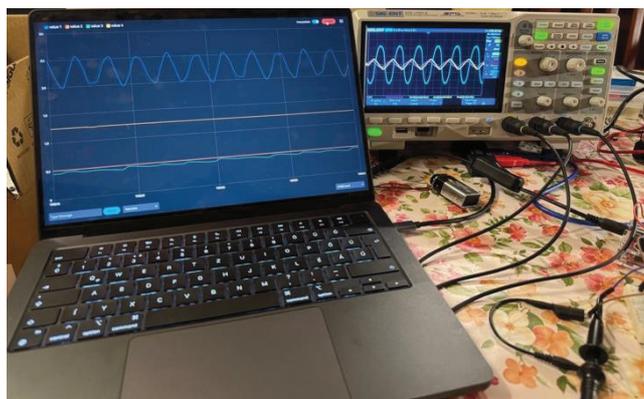


Figure 6: Input signal level equals to threshold level

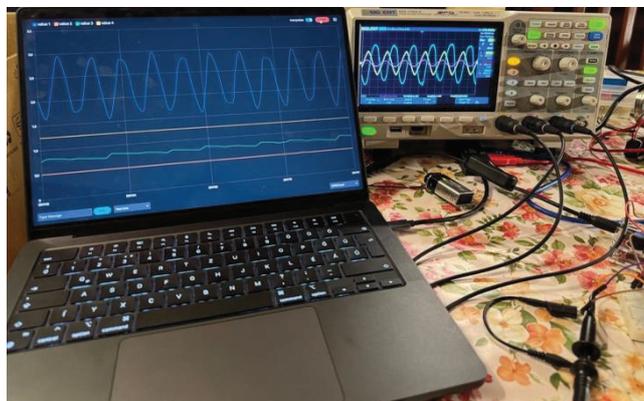


Figure 7: Input signal level is higher than threshold level v1

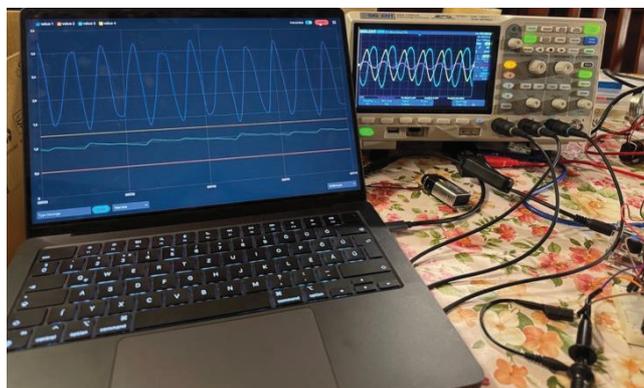


Figure 8: Input signal level is higher than threshold level v2

IV. EDUCATIONAL RELEVANCE

The implementation of an audio compressor effect with Automatic Gain Control on a microcontroller not only demonstrates a practical engineering solution but also provides substantial educational value in the training of electrical engineers. Embedded systems and digital signal processing are key areas of modern engineering curricula, and project-based assignments such as the presented system foster both theoretical understanding and practical skills.

By working on such projects, students gain hands-on experience with microcontroller programming, analog and digital circuit design, and real-time signal processing. The task integrates knowledge from multiple subjects, including electronics, systems theory, programming, and measurement techniques, thereby reinforcing an interdisciplinary engineering perspective. Moreover, troubleshooting during hardware implementation and software debugging develops essential problem-solving abilities and critical thinking, which are indispensable for professional engineering practice.

The project also supports the development of soft skills, such as project planning, documentation, and technical communication, since students are required to present results, interpret measurement data, and justify design decisions. These competencies are directly transferable to industrial applications, where embedded systems are widely employed in audio technology, telecommunications, and control engineering.

Consequently, the described implementation serves not only as a low-cost and effective solution for audio processing but also as a valuable educational tool. It enhances the engineering capabilities of students by combining theoretical knowledge with practical experimentation, preparing them for the challenges of modern embedded and signal processing systems.

CONCLUSION

The study demonstrated the successful implementation of an audio compressor effect using the Automatic Gain Control method on a microcontroller platform. The proposed system effectively stabilized output levels, reduced sudden volume fluctuations, and preserved the natural quality of the audio signal. By combining simple analog circuitry with efficient digital signal processing, the solution achieved low latency and reliable performance while maintaining low hardware costs. These results highlight the potential of microcontroller-based designs as practical and compact alternatives to conventional audio compressor units.

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Angular and Multipath Effects in Indoor Visible Light Communication Channels for Biomedical Monitoring Systems

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Abstract—The rapid advancement of medical technologies is driving the demand for reliable, energy-efficient, and secure systems capable of real-time health monitoring. The widespread deployment of light-emitting diode lighting systems opens up opportunities for the implementation of promising wireless optical communication technology - Visible Light Communication. This technology transmits data via visible light and offers several advantages over radio-frequency solutions. In the context of medical applications, this is high throughput, data privacy, and the absence of electromagnetic interference on the operation of sensitive medical equipment. However, its implementation is constrained by the requirement for a direct line-of-sight between the receiver and transmitter, and high sensitivity to external optical interference. The study presents models in line-of-sight and no-line-of-sight conditions indoors to assess data transmission parameters and identify factors affecting communication reliability. Using the OptiSystem simulation platform, the effect of emission and incidence angles, along with multipath signal propagation caused by surfaces reflections, we analyzed. The results allowed the determination of optimal emission and incidence angles ranges, and the assessment of the influence of the receiver field-of-view on system throughput.

Keywords—*visible light communications, optical wireless channel, health monitoring systems, multipath propagation, data transmission rate.*

I. INTRODUCTION

The development of modern technologies in the field of medicine requires the creation of highly accurate, energy-efficient and affordable solutions for monitoring human health in real time. At the state level, support for the digitalization of healthcare is carried out through national programs and initiatives aimed at increasing the availability of medical care and improving the quality of services provided.

According to the legislation of the Republic of Kazakhstan [1], the priority of the healthcare system is to protect the health of the population and form an infrastructure that ensures accurate and timely collection of information about patients.

Wireless radio frequency technologies such as Wi-Fi, Bluetooth, ZigBee are widely used in medical practice [2-5]. Telemedicine systems provide data transmission to remote devices, allowing doctors to promptly monitor the condition of patients and promptly respond to changes. Wireless infrastructure can also be used for remote consultations, access to electronic patient records, and data exchange

between medical institutions. This is especially important in conditions of limited access to medical care, for example, in remote regions or during self-isolation of patients. Modern technologies allow surgeons to perform operations remotely, controlling robots via a wireless connection. Radio frequency technologies facilitate the integration and interaction of various components of the information system, supporting the concept of the Internet of Things. This ensures centralized control and monitoring of equipment operation, reduces the likelihood of errors, and increases patient comfort.

Despite the active introduction of radio frequency technologies into medical systems, their use is associated with a number of limitations and potential risks. One of the significant disadvantages is the limited bandwidth of the radio frequency range, which prevents the simultaneous operation of a large number of devices in one network. In addition, these technologies are characterized by low noise immunity, sensitivity to the effects of other electronic devices, dependence on the density of repeater coverage and weather conditions. There is also a need to study the possible impact of electromagnetic radiation on human health, especially with long-term and intense exposure in clinical settings.

Of particular concern is the potential for electromagnetic interference with other critical equipment. If high-power transmitting devices are not used correctly, radio frequency interference may occur that could disrupt the functioning of medical equipment. This is especially true for life-sustaining equipment, such as ventilators. There is also a potential threat of disruption to the operation of implantable medical devices, such as pacemakers and neurostimulators, which are sensitive to radio frequency background.

In this regard, the wireless optical communication technology Visible Light Communication (VLC), which uses visible light to transmit data, is of interest. It has a number of key advantages over radio frequency solutions, especially in conditions where the use of RF radiation is limited or undesirable. The main advantages of VLC include high throughput, energy efficiency, wide range of available frequencies, the absence of electromagnetic interference, as well as the ability to accurately localize indoors and a high level of confidentiality of transmitted data. These characteristics make the technology relevant for use in health monitoring systems in hospitals, mobile medical centers and at home.

However, VLC technology has a number of limitations that hinder its implementation. These include the need for direct line of sight between the transmitter and receiver, sensitivity to interference from external light sources, limited transmission range, and the need for specialized infrastructure. To improve the efficiency and scale of application of such systems in healthcare, these technical barriers must be overcome, as well as solutions for integration with existing information and communication networks.

Previously, the authors conducted studies on the use of VLC technology for transmitting data of various formats. In [6], a system was presented and experimentally tested, including electronic circuits of a transmitter and receiver, designed to transmit audio signals using a white light-emitting diode (LED) in conditions of limited natural light. In [7], the transmission of symbolic data between two personal computers was implemented using a similar source and physical encoding methods. In [8], an experimental system for transmitting current room temperature values using LED lighting is presented. The system provided bidirectional communication for transmitting data and control signals to maintain a given temperature. The transmission error was hundredths of a fraction. The experimental results confirmed stable operation system while maintaining the level of illumination and visual comfort.

This study is a logical continuation of previous scientific works and is focused on the creation of simulation models of a wireless optical communication channel using visible light in order to evaluate data transmission parameters and analyze the applicability of the technology in human health monitoring systems.

Thus, the implementation of the set goal will allow us to substantiate the main parameters of the optical communication channel to ensure reliable transmission of information, determine the influence of external factors on the characteristics of the signal, and also formulate recommendations for the use of VLC technology in medical practice, including mobile and stationary monitoring systems.

II. ANALYSIS OF THE APPLICATION OF VLC TECHNOLOGY IN MEDICAL MONITORING SYSTEMS

To assess the potential of VLC technology in medical applications, it is necessary to analyze system architectures, data transmission models, and identify existing limitations and promising development directions.

The article [9] proposes a system for transmitting patient biomedical data using white LED illumination via a downlink. The system provides transmission of two types of data: text information about the patient and analog signals of physiological parameters in real time. The HL7 protocol is used for transmission. This standard is accredited by the American National Standards Institute for the confidentiality of medical data. The On-Off Keying (OOK) method is selected as a modulation. A data transmission rate of 56 kbit/s and a bit error rate of 1×10^{-6} at a distance of 0.5 meters without the use of collimating optics are achieved. Also, experiments have shown the possibility of data transmission with a decrease in the illumination level to 90% of the nominal optical power of the light source.

The article [10] describes a static patient monitoring system using an uplink data transmission channel in the visible range. Studies related to external interference from ceiling and natural lighting were conducted. Photodetectors in the system are placed in such a way as to minimize the impact of ceiling lamps on signal reception. The experimental setup was pre-loaded with data on human physiological parameters, including electrocardiogram (ECG), body temperature and heart rate. The data were transmitted using OOK modulation. The emitter LED was located at a distance of 130 cm in direct visibility from the receivers installed at an interval of 20 cm. The low transmission rate of 10 bit/s is explained by the use of a low-power LED. According to the authors, this value is sufficient for data transmission in the specified mode.

The correctness of VLC systems in medical applications was considered in [11]. Wireless data transmission via Wi-Fi and via a visible light channel was compared. An experimental setup for patient ECG monitoring showed an error in data transmission via VLC within 3%. The signal was received with minor distortions associated with the experimental conditions. The possibility of stable data transmission at a distance of up to 2 meters between the receiving and transmitting devices was recorded.

The use of RGB LEDs in such systems allows for increased reliability and accuracy due to three-channel communication [12]. However, it should be noted that such systems are much more difficult to implement. In [13], an RGB LED and a color sensor were used to simplify the system design, allowing signals to be separated into color channels on the receiving side. An active low-pass filter was used to suppress background light, after which the signal was demodulated using a microcontroller and stored on a database server in real time. The wavelength division multiplexing principle allowed three different signals (ECG, photoplethysmogram, body temperature) to be transmitted simultaneously over a distance of 11 meters with a PER of 5×10^{-6} .

The existing limitations of VLC systems necessitate their integration with radio frequency (RF) technologies. In [14], hybrid optical-RF architecture is proposed as a means to overcome the constraints of VLC and improve overall performance. Hybrid networks provide better coverage and communication reliability by utilizing VLC in line-of-sight areas and RF to support communication in blind zones.

The analysis shows that most VLC systems aimed at medical applications use OOK modulation. In addition, such systems usually require direct visibility between the transmitter and receiver. The signal quality is significantly affected by external optical interference from both natural light and neighboring lighting fixtures. These features emphasize the importance of the optical channel design stage, the choice of adequate modulation methods, and create prerequisites for the development of hybrid solutions using radio frequency technologies.

The efficiency of indoor optical wireless communication depends on the lighting system parameters and the characteristics of optical signal propagation. The geometry of the transmitter and receiver arrangement as well as the angles of emission and reception, significantly affects the channel characteristics due to the inverse square law of distance and Law of Lambert of diffusion.

In this regard, this study focuses on the analysis of the influence of geometric parameters on the characteristics of the optical channel. Understanding these aspects allows us to more accurately model the behavior of VLC systems and optimize the placement of transmitting and receiving devices to ensure reliable transmission of biomedical data.

III. MODELING OF INDOOR WIRELESS OPTICAL COMMUNICATION CHANNELS

In the process of taking biomedical parameters, there may be situations in which the LED transmitting the data and the photodetector are not located strictly on the same optical axis, i.e. the angle of deviation from the line of sight differs from zero. To assess the signal quality, we will consider the effect of the emission and incidence angles in the indoor line-of-sight (LOS) propagation model.

The geometric model of optical signal propagation under LOS conditions is illustrated in Fig. 1. In this model, d is the distance between the LED and the photodetector, φ is the LED emission angle relative to its axis, $\Phi_{1/2}$ is the LED half-power emission angle, FOV is the field-of-view photodetector, ψ is the photodetector incidence angle. A two-dimensional room model with a height of 3m and a length of 5m is considered. An LED serves as the transmitter, while photodiode functions as the receiver. The field of view of the photodetector and the half-power emission angle of the model are set to 70° .

Fig. 2 shows a simulation model developed in the OptiSystem software environment for studying the properties of a transmitted signal in an optical wireless system under line-of-sight conditions. The presented model is not connected to real data, so a bit sequence generator is used. The generated data are converted into an electrical signal of the non-return-to-zero (NRZ) format, displayed on an oscilloscope for monitoring. The LED modulates the signal into an optical one and transmits it through a diffuse channel to a photodetector.

The received light signal is converted back into an electrical signal, after which it passes through a low-pass Bessel filter to suppress high-frequency noise. At this stage, a check is performed using a second oscilloscope. Then, the regenerator performs signal reshaping, retiming, and amplification to compensate for distortions. At the final stage, the error analyzer compares the restored signal with the original bit sequence, assessing the transmission accuracy.

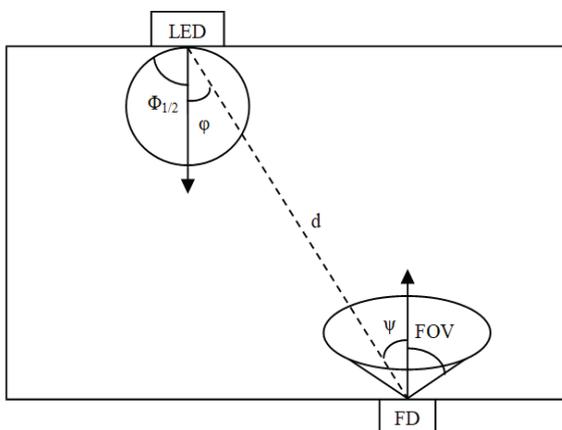


Fig. 1. Geometric model of optical signal propagation in LOS channel

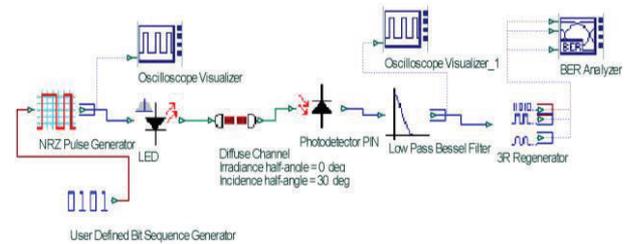


Fig. 2. Simulation model LOS channel

The study analyzed the influence of the angles of emission and incidence in the LOS propagation model. At the first stage of modeling, the angle of incidence was fixed at 30° , and the angle of emission varied from 0 to 50° . Then, conversely, the angle of emission was set at a constant value of 30° , and the angle of incidence varied from 0 to 50° . Fig. 3 shows the results for all modeling options.

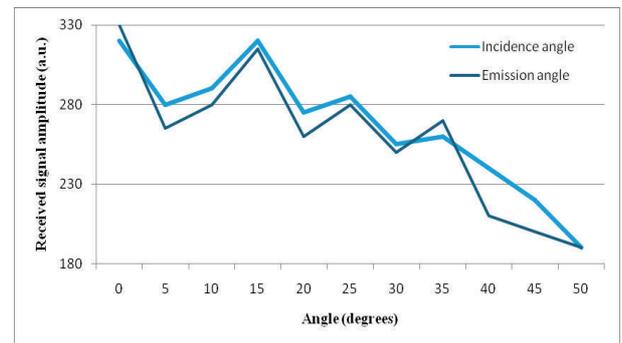


Fig. 3. The influence of the angle on the amplitude of the received signal

The graph demonstrates the dependence of the received signal amplitude on the deviation angles of the source and receiver. In the range up to 15° , amplitude fluctuations are observed, probably due to the peculiarities of the optical flow distribution and the sensitivity of the receiving surface. The maximum amplitude is achieved at minimum angles, after which a gradual and then more pronounced signal decrease are observed. In the range from 30° to 50° , the signal amplitude steadily decreases, regardless of whether the emission angle or the incidence angle changes, which indicates signal degradation when deviating from the optical axis. Both curves almost coincide, which may indicate a symmetrical effect of deviation angles on the resulting signal power.

This confirms that the VLC system is most resistant to distortions at small angles up to 20° and loses efficiency at values above 30° , which is important to consider when designing and positioning system components. The results confirm that, to ensure reliable data transmission in VLC systems, it is necessary to account for the spatial arrangement of the transmitter and receiver and to minimize angular deviation from the LOS direction.

The situation when the LED and photodiode are located strictly on the same line is relatively rare due to the limitations and features of the interior architecture of the premises. However, even with direct visibility between the source and receiver, in most scenarios the internal optical communication line is characterized by multipath propagation. This is due to the fact that part of the emission from the LED is reflected from the walls, ceiling and other surfaces, forming additional components of the signal.

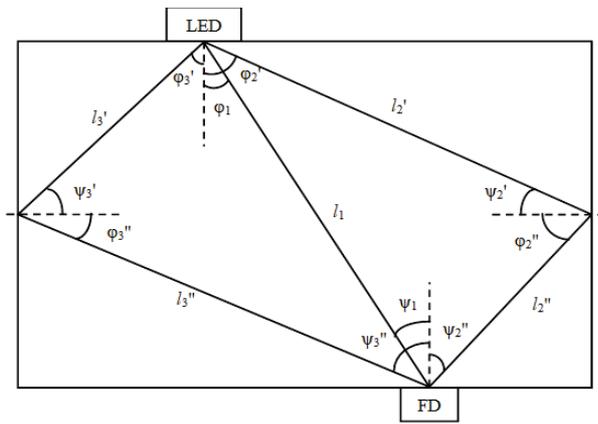


Fig. 4. The influence of the angle on the amplitude of the received signal

Therefore, for visible optical communication systems, a scenario is of particular interest when the signal reaches the receiving device both along a direct path and due to reflections from related surfaces.

The geometric model considering multipath propagation is shown in Fig. 4. In this configuration, the LED emits the primary signal propagating directly to the photodetector (ray l_1), as well as two reflected signals (rays l_2 and l_3) formed as a result of walls reflections. Each path is characterized by its own pair of emission angles ϕ_i and incidence ψ_i , and by its path length l_i , which affects signal attenuation.

For the analysis, the numerical values of angles and distances parameters given in Table 1 are used.

TABLE I. MODEL PARAMETERS

Path length	Emission angle	Incidence angle
$l_1 = 3,3$ m	$\phi_1 = 26^\circ$	$\psi_1 = 26^\circ$
$l_2' = 3,5$ m	$\phi_2' = 65^\circ$	$\psi_2' = 22^\circ$
$l_2'' = 3,6$ m	$\phi_2'' = 38^\circ$	$\psi_2'' = 51^\circ$
$l_3' = 2,8$ m	$\phi_3' = 55^\circ$	$\psi_3' = 35^\circ$
$l_3'' = 3,1$ m	$\phi_3'' = 32^\circ$	$\psi_3'' = 55^\circ$

The simulation model of a wireless optical communication channel under conditions of multipath propagation of light is developed based on the previous model. The difference lies in the addition of reflection simulation (Fig. 5).

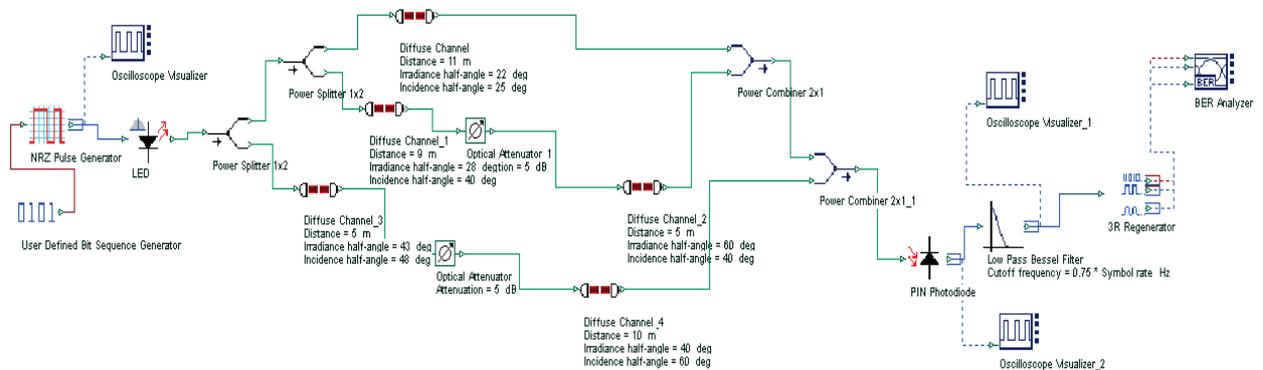


Fig. 5. Simulation model NLOS channel with multipath propagation

For this purpose, an Optical Attenuator block with 5 dB attenuation at the reflection point is used. A Power Splitter block is used to split the input optical signal into several output ports with specified power division factors. Before sending the signal to the photodetector, it is necessary to use the Power Combiner block to combine the optical signals into one output. To clean the signal from extraneous noise, in our case additional noise from reflection, we use a low-pass filter.

The model provides the ability to obtain waveforms signals: the generated input signal supplied to the LED; the signal recorded by the PIN diode; the signal after passing through the low-pass Bessel filter.

The input signal (Fig. 6a) demonstrates an ideal digital pulse shape. Its amplitude is stable, the fronts are sharp, and the noise level is minimal. This confirms the correct operation of the bit sequence generator and NRZ pulse modulation.

The received signal (Fig. 6b) is heavily distorted compared to the original. Amplitude fluctuations, overlaps, spikes, and a characteristic pulse broadening effect typical of multipath propagation are observed. The causes of the distortions are reflections from the walls, which occur due to the fact that each channel in the model has different emission and incidence angles, and varying transmission distances. Notably, emission/incidence angles greater 30 degrees in channels contribute to energy dispersion and increase the delays between reflected signal components. This, in turn, intensifies interference and leads to significant distortion of the received signal.

The filtered signal (Fig. 6c) exhibits an improved waveform compared to the unprocessed signal, with partial restoration of the rectangular pulse structure. Although high-frequency noise is partially mitigated, residual distortions persist, indicating incomplete suppression of multipath effects and the limited effectiveness of the applied filtering. Potential improvements to the model may include implementing an equalizer after the low-pass filter, as well as employing adaptive digital filters capable of dynamically adjusting to the multipath propagation conditions in real time. The simulation results show that the angular parameters of the channel significantly affect the shape of the output signal, which is especially important for VLC systems under multipath propagation conditions.

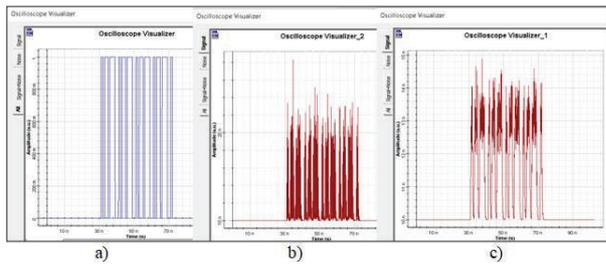


Fig. 6. Signal waveforms: generated input signal (a); signal received by the photodetector (b); filtered signal (c).

At the next stage, an analysis of the dependence of the data rate on the FOV angle of the photodetector was performed to estimate the channel capacity under multipath propagation conditions. Based on the data in Table 1 and the parameters of the room model, the transmission rate was calculated for different FOV values using an approximate relationship between the transmission rate and the root-mean-square (RMS) delay spread, which characterizes the level of intersymbol interference [15].

Analysis of the obtained results (Fig. 7) shows that increasing FOV of the receiver leads to a higher bit rate: from 5.12×10^7 bit/s at $\text{FOV}=30^\circ$ to 7.48×10^7 bit/s at the set maximum $\text{FOV}=90^\circ$. This can be explained by the fact that a wider field of view allows the receiver captures more reflected signal components, thereby increasing the total received power and, consequently, improving data transmission performance.

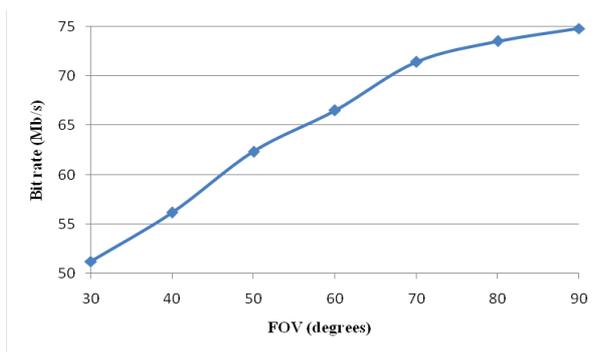


Fig. 7. The influence FOV of the receiver on the data transmission rate

The obtained data rate values are sufficient for most standard applications in household and industrial environments, such as text transmission, equipment control, sensor networks and IoT applications.

IV. CONCLUSION

The modeling of optical wireless communication using a LED source was carried out. The models of optical signal propagation under the LOS and NLOS conditions indoor environment with given geometric dimensions and angular parameters of the transmitting and receiving devices were considered. In the LOS model, it was found that the optimal operating ranges of radiation and reception angles are 20° - 35° , at which the signal amplitude remains stable. In the NLOS model, taking into account multipath propagation, significant signal distortions and a high noise level are observed. After applying filtering, the signal shape was partially restored. In addition, the effect of the FOV on the data transfer rate was studied. With a viewing angle of 30° , the calculated data transfer rate was 51 Mb/s, which is sufficient for transmitting biomedical data.

The results obtained confirm the promise of VLC technology for medical applications, and taking into account multipath signal reflections and the introduction of adaptive receiver orientation mechanisms can increase the reliability and stability of transmission in real operating conditions. It should be noted that this study did not consider the influence of interference from external light sources and adjacent transmission channels, which is an area for further research.

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Accuracy Assessment of CatBoost for Storm Damage

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Abstract—This paper explores the use of gradient boosting to quantify the economic damage caused by storms and classify storm events as severe or mild. The study draws on a historical disaster open database. These figures confirm gradient boosting’s high accuracy in analysing extreme meteorological events for insurance.

Keywords— *CatBoost, storm-damage regression, storm-intensity classification, machine learning.*

I. INTRODUCTION

Global warming is intensifying the frequency and economic impact of extreme weather phenomena—hurricanes, typhoons, and storms. Accurate forecasting of damage magnitude and early identification of high-risk events are becoming critical. Modern AI and machine-learning techniques, especially boosting algorithms, have proved highly effective on tabular data [2, 4]. CatBoost, developed by Yandex and optimised for categorical features through ordered boosting, consistently outperforms other gradient-boosting implementations and has been successfully applied to climate-risk problems. In this study we deploy CatBoost to predict monetary storm losses and to flag events whose damage exceeds US\$ 100 million. The aim is to demonstrate CatBoost’s practical value for climate-disaster analytics and to benchmark its predictive performance [3, 13].

In this study, we leverage CatBoost to tackle two complementary disaster-analytics tasks using a historical storm disaster database: (i) a regression task to predict the monetary damage caused by individual storm events, and (ii) a classification task to flag “severe” storms, defined here as those causing losses above 100 million US. The goal is to assess CatBoost’s accuracy and practical value in predicting storm impacts, while developing a robust modeling pipeline that spans data preprocessing, model training, and evaluation for both continuous and binary outcomes. By addressing both the magnitude of losses and a threshold-based intensity categorization, the approach provides a more holistic analysis of storm risk than either task alone. This dual focus is particularly important for translating predictive analytics into decision-making: precise loss estimates inform resource allocation and insurance/recovery planning, whereas early classification of high-damage events can trigger timely alerts and disaster response escalation. Moreover, our work fills a gap in the literature – whereas many prior studies apply CatBoost (and similar ML models) to hazard susceptibility mapping or event outcome classification, few have addressed direct economic loss regression for storms, especially in conjunction with an intensity classification. By benchmarking CatBoost on these tasks, we contribute evidence of its

effectiveness in climate-disaster contexts and identify strengths and limitations of this approach.

The remainder of the paper is organized as follows. Section 2 describes the data and methodology, including preprocessing steps and CatBoost model setup for both regression and classification. Section 3 presents the results, with performance metrics evaluating the accuracy of damage predictions and severity classification. In Section 3, we provide an in-depth discussion of these results in the context of related work, comparing our approach and findings with recent studies on hazard prediction and classification using CatBoost and hybrid techniques. We highlight the novel aspects of our pipeline and discuss practical implications, such as integration into early warning systems and urban resilience frameworks. Finally, Section 4 concludes the paper with a summary of findings and future research directions.

II. METHOD

Data Source and Preparation. We used a global historical disaster database (1902–2025) filtered for storm-related events (including hurricanes, cyclones, and severe storms) with complete information on occurrence year, country, disaster subtype, and total economic damage [1]. After filtering, a total of 967 storm events remained. Each record includes the Total Damage (reported losses, in thousand USD), which serves as the target for the regression task. We created a binary label for each event indicating whether its total damage exceeded \$100 million (label “1” for severe events) or not (label “0” for mild events); in our dataset, 348 events (36%) are severe and 619 (64%) are mild according to this threshold. This class distribution, while moderately imbalanced, still provides a substantial number of high-impact cases to learn from. Several other features were available (e.g. number of people affected, insured losses, etc.), but many had missing values. We elected to retain these features by imputing missing numeric values as zero, acknowledging this as a conservative assumption (i.e. treating unknown losses or counts as zero could underestimate those impacts). This imputation strategy avoids dropping records and lets the model potentially infer patterns even from sparse data. Each event’s Country and Disaster Subtype (e.g. hurricane, convective storm, etc.) were treated as categorical features; CatBoost can directly handle such features without one-hot encoding, so we included these in the model’s categorical feature list. By incorporating country and subtype, the model can capture region-specific economic factors or differences in storm types (for example, that tropical cyclones in certain regions tend to cause higher damages due to exposure of coastal assets). The data was split into a training set (80% of events, $n \approx 773$) and test set (20%, $n \approx 194$), using a

fixed random seed to ensure reproducibility. The chronological span of the data (over a century) means there could be non-stationarity (e.g. growth of exposed infrastructure over time); however, given the relatively small number of samples, we opted for a random split rather than strict chronological split, under the assumption that the model can capture time-related trends if the year is implicitly represented through the data (to be explored in future work).

CatBoost Model Setup. We trained separate models for each task: a CatBoostRegressor for predicting continuous damage, and a CatBoostClassifier for the binary intensity classification. Both models were trained with similar hyperparameter settings that were tuned informally based on validation performance on the training set. In particular, we set the number of boosting iterations (trees) to 500 for both models, which we found sufficient for convergence. A relatively small learning rate of 0.05 was used to ensure stable learning. Tree depth was capped at 6 levels, balancing model complexity against the risk of overfitting (depth 6 is usually adequate given the number of features and size of our dataset). We enabled CatBoost’s built-in handling of categorical features (with order-driven target encoding and per-fold permutations) by specifying the categorical feature indices. Other parameters were left at CatBoost defaults or chosen to mirror typical best practices (e.g. L2 leaf regularization was applied as per default to avoid overfitting; an early stopping criterion monitored the loss on a validation split, stopping if no improvement for 50 iterations). Importantly, for the classification model, we set the evaluation metric to the area under the ROC curve (ROC-AUC) during training. Given the slightly imbalanced classes, optimizing for ROC-AUC (which is insensitive to the exact threshold and focuses on ranking quality) is more appropriate than raw accuracy. We did not apply any class weighting or oversampling in this baseline model; the proportion of severe events (36%) is significant enough that the model can learn from them, though we acknowledge that techniques to handle imbalance could further improve recall for the minority class (as discussed later). Feature importance was evaluated after training to verify that known drivers (like storm type or country, which may proxy for region-specific exposure) were among influential features, providing face validity to the model.

Performance Evaluation. We evaluated the regression model using standard error metrics and variance-explained metrics: specifically, the Mean Absolute Error (MAE) to gauge average prediction error in monetary terms, and the coefficient of determination (R^2) to assess the proportion of variance in storm losses explained by the model. MAE is reported in the same units as the target (thousand USD, which we convert to a more interpretable scale), and R^2 is unitless between 0 and 1. For the classification model, we computed overall accuracy (the fraction of correctly classified events), as well as precision, recall, and F1-score for each class (severe and mild), to ensure the model’s performance is balanced and that it is not, for example, neglecting the minority severe class. The ROC curve and corresponding AUC were also obtained on the test set; the ROC-AUC offers a threshold-independent measure of discrimination ability (with 0.5 meaning no better than chance and 1.0 indicating perfect separation of severe vs mild). We present a confusion matrix to illustrate how the model’s predictions are distributed (true positives, false negatives, etc.), which helps identify any bias (e.g., if false negatives – severe storms misclassified as mild – are particularly frequent, that would be concerning for an early

warning application). All results reported are on the hold-out test set (not seen during training), to provide an unbiased assessment of model generalization.

By designing the modelling pipeline in this way, we ensure that our evaluation covers both quantitative accuracy (are the predicted loss values close to actual? is the classification of severity correct for most events?) and practical relevance (does the classifier capture most of the truly severe events with acceptable false alarm rates? are the error margins on loss predictions reasonable for decision-making?). In the next section, we present the results of the CatBoost models on the test data, demonstrating its performance on both tasks.

III. RESULTS

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In the regression task, CatBoost achieved an MAE of $\approx 342\,400$ (thousand USD) and an R^2 of ≈ 0.54 on the test set. This means the model explains about 54 % of the variance in storm-related economic losses.

For the “strong / weak storm” classification, the model reached an accuracy of $\sim 74\%$, with a ROC-AUC of ~ 0.78 . An AUC of ≈ 0.78 indicates good risk ranking quality (the closer to 1, the more accurate the classifier [2]). A fragment of the classification report (precision / recall / F1 and support for each class) is shown below Table 1.

TABLE I. TABLE OF ACCURACY METRICS

Class	Accuracy Metrics		
	Precision	Recall	F1
Weak storm (not strong)	0.80	0.82	0.81
Strong storm (sever event)	0.67	0.64	0.66

Latin or Greek characters in italics are used for physical symbols and normal characters for measuring units and numerical values. Text in figures is also written with normal letters. Aggregate metrics: accuracy ≈ 0.74 , ROC-AUC ≈ 0.78 . The confusion matrix and ROC curve are presented in Figures 1–2.

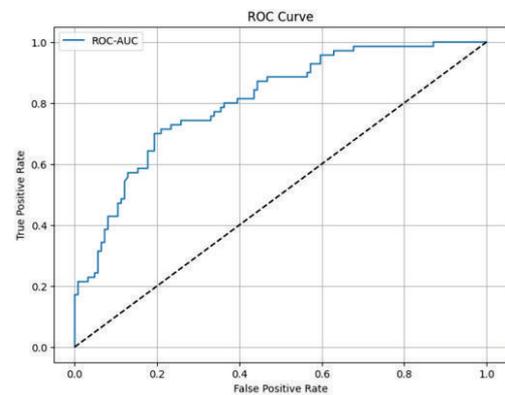


Fig. 1. ROC curve of the CatBoost classifier (AUC = 0.78) for distinguishing strong storms.

Figure 1 shows the classifier’s ROC curve (X-axis — false-positive rate, Y-axis — true-positive rate; dashed line — random guess). The figure illustrates that the model markedly

outperforms random guessing and can identify most “strong” storms (AUC = 0.78).

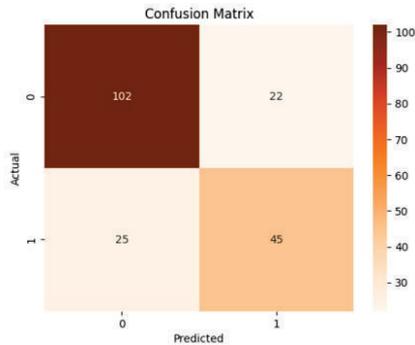


Fig. 2. Confusion matrix.

Figure 2 displays the confusion matrix (distribution of classification errors): it can be seen that the model is less likely to label a weak storm as “strong” than the other way around.

Our CatBoost-based approach for storm damage prediction and intensity classification can be viewed in the context of a broader trend of applying advanced ML models to natural hazard risk assessment. The results of this study corroborate findings from and extend prior work across multiple disaster domains. In a recent review of climate multi-hazard modelling, Ferrario et al. (2025) highlighted the growing adoption of machine learning and ensemble methods for risk analysis [7]. They noted that boosting algorithms (like CatBoost) are increasingly used to model complex, non-linear hazard–impact relationships, trained on historical disaster impacts to predict future risks. Our work exemplifies this trend by training on a century of storm loss data (past impacts) to predict both the magnitude and severity of future storm losses, effectively using supervised ML on past impacts to model future risk, which Ferrario et al. identified as a significant emerging area. Moreover, our focus on integrating data (disaster records with categorical features for region and type) and producing straightforward predictive models aligns with the review’s observation that ensemble ML methods are a staple for current risk analysis efforts. Ferrario et al. also emphasize the importance of explainable AI (XAI) in this field, as well as the need to incorporate multi-hazard interactions and dynamic vulnerability factors in future models [8]. While our study deals with a single hazard type (storms) and a relatively static dataset (aggregated historical losses), we acknowledge these points: integrating explainability (for instance, using SHAP values to interpret the CatBoost model’s predictions) would enhance trust and practical utility, and is a logical next step. Similarly, our approach could be extended to consider compound events (e.g. storms causing flooding) or evolving exposure (e.g. increasing coastal development) to address multi-hazard interactions and dynamic vulnerability, as recommended for advancing the field. In summary, the methodology and goals of our study are well-aligned with contemporary directions in climate risk modelling: use of ensemble ML for improved predictive accuracy and an eye toward future expansion into more complex, integrated assessments and operational early warning systems.

Considering specific applications of CatBoost in hazard modelling, our work bridges both regression and classification tasks, whereas many studies focus on one or the other. In the

realm of binary classification for imbalanced disaster outcomes, CatBoost has proven highly effective, especially when augmented with techniques to address class imbalance. He et al. (2024) introduced a GA-CatBoost-Weight algorithm for predicting whether terrorist attacks result in casualties [6].

The primary contribution of this work is the development of a comprehensive modelling pipeline that leverages a single advanced ML algorithm (CatBoost) to address two critical aspects of storm disaster analysis: predicting the amount of economic damage (regression) and predicting the severity class of the event (classification based on a damage threshold). By doing so, we illustrate that a data-driven approach can effectively quantify risk in absolute terms and also make qualitative judgments about an event’s impact level. This dual capability is novel compared to most existing studies, which typically focus on either estimating hazard likelihood/impact or classifying events into categories, but not both in tandem. The pipeline covers all stages from data pre-processing (handling missing data, encoding categorical features), through model training (with appropriate hyperparameter choices and validation), to evaluation with relevant metrics for each task, providing a template that could be applied or extended to similar problems (e.g., other hazards or other impact metrics like casualties).

The implications of this work are directly relevant to operational disaster risk management. An immediate real-world application is in early warning systems for storms. Traditional early warnings are based on meteorological forecasts (track, wind speed, category) and qualitative assessments of vulnerability. By incorporating a model like ours, agencies can generate an impact-based forecast – i.e., not just predicting the storm’s physical parameters, but also estimating the likely economic damage. This aligns with a paradigm shift in many meteorological services toward impact-based warnings (for example, saying “Storm X is expected to cause extensive damage and losses in excess of Y” rather than just “Storm X will make landfall with winds of Z mph”). Our classification model, in particular, could be used to trigger alerts: if the model predicts an incoming storm is severe (probability above a certain threshold), authorities might activate emergency plans, evacuations, or international assistance mechanisms sooner. Importantly, our model uses information that is often available early (storm type, general location which maps to country, historical analogues) and could potentially ingest near-real-time forecasts (if we link, say, forecasted wind speed or pressure as an input feature) to update the predictions as an event evolves. The relatively high recall for severe storms means it would rarely miss flagging a truly disastrous storm, which is crucial for warnings. False alarms, while not negligible, are at a level that can be handled through effective communication (a ~15% chance that a “severe” warning might not pan out could be acceptable if communicated with uncertainty, and is likely lower than the false alarm rates of some weather forecasts themselves). Ferrario et al. (2025) stress that open data and ML advances should feed into AI-driven early warning systems – our study is a step in that direction, showing how historical disaster data can be mined to provide a predictive warning tool.

IV. CONCLUSIONS

This paper presented an in-depth accuracy assessment of using the CatBoost algorithm for two critical tasks in storm impact modelling: regression of economic damage and binary classification of storm severity based on a \$100 million loss

threshold. Trained on over a century of global storm disaster data, the CatBoost models achieved solid performance – explaining more than half the variance in storm losses and correctly identifying a large majority of the high-impact events. These results attest to CatBoost’s effectiveness and versatility in handling heterogeneous disaster data for both continuous and categorical prediction objectives. Through a detailed methodological walkthrough and comparison with related studies, we highlighted how our approach aligns with state-of-the-art applications of machine learning in hazard risk assessment, while also pushing the envelope by combining regression and classification in one pipeline. Our findings reinforce that ensemble tree-based models like CatBoost are invaluable tools in climate disaster analytics, offering high accuracy and the ability to incorporate diverse features (including categorical descriptors often present in disaster records) [14]. In a broader perspective, this work contributes a case study toward impact-based forecasting and data-driven early warning capabilities. By translating historical disaster data into predictive insights, such models enable a shift from reactive disaster response to proactive risk management. The study’s dual-focus pipeline is especially relevant for operational use: it provides both the likely magnitude of losses and an easy-to-interpret tag for severity, which can be directly used to trigger disaster preparedness protocols. In comparing our approach to existing literature, we found common evidence that boosting algorithms enhanced with domain knowledge or hybrid techniques yield top-tier performance in various hazard contexts (foods, landslides, multi-hazards) [5, 10, 11]. This cross-validation of CatBoost’s utility bolsters confidence in our chosen methods. Moreover, we emphasize that our study’s novelty lies in bridging a gap: integrating economic loss prediction with intensity classification within one consistent modelling framework. Few studies have attempted to predict actual monetary damages with ML; our success in doing so opens the door for further research to refine these predictions (for example, by incorporating real-time meteorological inputs or macroeconomic exposure data). It also invites exploration into generalizing the approach to other regions or perils.

Looking ahead, we advocate for several enhancements, including coupling our CatBoost models with explainable AI techniques to better interpret and communicate their predictions, and integrating them into comprehensive multi-hazard early warning systems as suggested by recent reviews [9, 12]. We also see potential in collaborating with domain experts to inject more physics-based features into the model (bridging purely data-driven and physics-informed modelling). Such interdisciplinary efforts could address some limitations of the current approach, like its reliance on historical patterns in a non-stationary climate regime.

In summary, the study demonstrates that a robust ML pipeline – from data pre-processing to model evaluation – can be built around CatBoost to effectively predict storm damages and classify event severity. These tools, used in conjunction with traditional forecasting and expert knowledge, can significantly enhance our ability to prepare for and mitigate the adverse effects of extreme storms. As climate change continues to amplify weather extremes, developing and deploying such data-driven predictive analytics will be an essential component of building resilient communities and reducing the economic toll of disasters. Our work contributes to this endeavour by providing both a template for

implementation and a benchmark of achievable accuracy, against which future innovations in the field can be measured.

The study shows that CatBoost can be effectively applied to forecasting the economic damage caused by storms and to classifying their intensity. The model delivers acceptable accuracy ($R^2 \approx 0.54$, $MAE \approx 3.4 \times 10^5$ thousand USD) for the loss-regression task and achieves a high ROC-AUC ≈ 0.78 for the classification task. These results confirm the promise of boosting methods for analysing extreme climate events, as supported by recent research [2, 3].

The practical value of the model lies in the ability to integrate its outputs (damage estimates and classification results) into early-warning systems and into planning measures to reduce storm risks. Future work should enlarge the dataset (for example, by adding alternative criteria for defining a “strong storm”) and explore the model’s interpretability (e.g., via XAI methods) to identify the key factors driving damage [2].

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PET bottle recycling and filament production for 3D printing: design and development of a sustainable extrusion system

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Abstract— The widespread use of plastics, particularly polyethylene terephthalate (PET), has created both economic opportunities and severe environmental challenges. As plastic consumption continues to rise globally, innovative recycling and reuse strategies become essential to mitigate the ecological burden of plastic waste. One promising approach is the repurposing of PET bottles into usable 3D printing filament, thereby transforming waste into value-added products. This paper presents the design and development of a PET recycling and filament manufacturing system for 3D printers. The work integrates knowledge of polymer chemistry, thermomechanical design, and additive manufacturing, with an emphasis on environmental awareness and sustainability. The system is designed to cut, shred, and extrude PET waste into filament suitable for Fused Deposition Modeling (FDM) printers. Experimental results demonstrate the feasibility of producing consistent filament diameters with acceptable mechanical performance, though several material-related challenges remain. This study contributes to circular economy practices by promoting localized recycling, enabling decentralized filament production, and reducing both environmental impact and raw material costs.

Keywords— PET, plastics, 3D print, environment

I. INTRODUCTION

Since their invention in the 1860s, plastics have revolutionized the manufacturing industry. In the mid-19th century, scientists were searching for a low-cost synthetic compound that could replace natural materials, which at the time were both expensive and difficult to produce. Over the decades, increasingly complex plastics were developed, and today these materials are integrated into nearly every aspect of modern life, from clothing and furniture to the automotive industry. In fact, contemporary society is fundamentally built upon plastics. However, this advancement comes at a cost: plastics are highly durable materials, making them extremely difficult to recycle without causing environmental harm [1].

Natural polymers have long existed as part of the environment. For instance, rubber, a naturally occurring polymer, was already in use during the 11th century by the Maya civilization for making balls used in ritual games. The basis of all plastics is the macromolecule, a structure composed of repeating identical units. The starting material is the monomer, which can be considered the fundamental molecular unit representing the full chemical structure. Polymers are formed by the aggregation of such repeating

macromolecules. In scientific terminology, the word "polymer" typically refers to both natural and synthetic materials, whereas "plastic" is more commonly used when referring specifically to artificially produced polymers [2]. Figure 1 shows the chemical composition of PET [3].

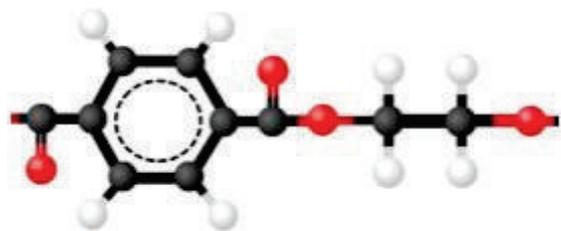


Fig. 1. Chemical structure of PET [4]

One of the most widely used synthetic polymers is PET, the abbreviation of polyethylene terephthalate, a name derived from its chemical composition. Its molecular formula is $C_{10}H_8O_4$, consisting of 10 carbon atoms, 8 hydrogen atoms, and 4 oxygen atoms. PET is synthesized through a polycondensation process and belongs to the category of linear thermoplastic polyesters. Within the group of saturated thermoplastic polymers, it is classified as having a crystalline structure. While semi crystalline or crystalline plastics are generally opaque, PET can exhibit transparency due to the fact that its crystal lattice is smaller than the wavelength of visible light. Figure 2 is an example for polymer usage.



Fig. 2. Polymer particle toys [5]

PET loses mechanical strength at approximately 70–75°C, referred to as the crystallization temperature, and melts at around 210–270°C. Owing to these properties, it is easily moldable: when cooled rapidly, it solidifies into an amorphous structure, while slow cooling allows it to form an ordered crystalline arrangement. In its solid state, PET demonstrates high impact resistance and strong chemical stability, making it suitable for storing oils, acids, alkalis, and hydrocarbons. For this reason, PET has become a key industrial material, widely employed in the manufacturing of containers and bottles. Additionally, because it is largely resistant to microorganisms and various forms of radiation, it is particularly suitable for food packaging applications.

The production process of PET bottles involves first creating a preform resembling the final product, followed by expansion through injection blow molding. In this process, the molten polymer is injected into a mold, where it assumes the required shape. Once cooled, the resulting product is immediately ready for practical use. PET is also highly compatible with 3D printing technologies, where it is applied in the production of models and prototypes. Figure 3 introduces the worldwide PET recycling and production [6].

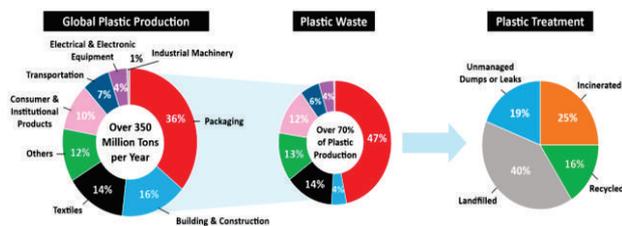


Fig. 3. Global plastic production and recycling [6]

Nevertheless, despite its many advantageous properties, PET poses a significant environmental challenge. Due to its high durability and resistance to degradation, it persists in nature for extended periods. PET waste can remain in the environment for up to half a century, with consequences that extend across multiple future generations. Figure 4 demonstrates the possible degradation of PET material.

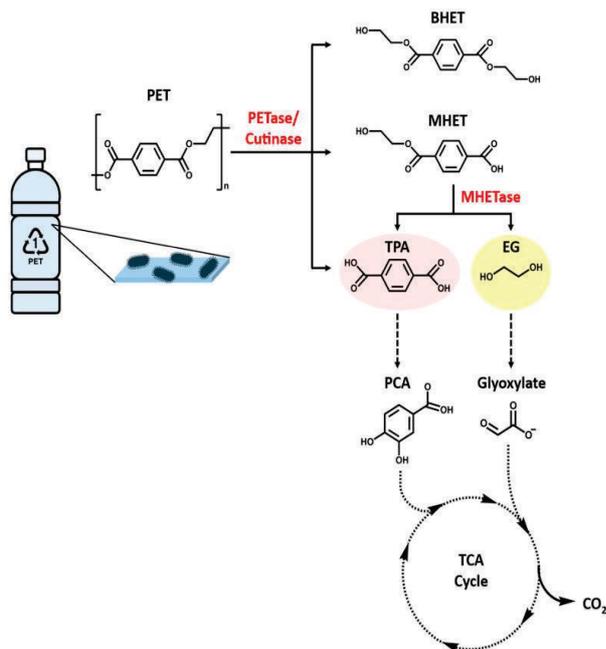


Fig. 4. Microbial degradation of PET [6]

This paper addresses both environmental and technological challenges by proposing a system for transforming PET bottles into usable filament for 3D printers. By bridging polymer recycling with additive manufacturing, this approach has the potential to support local circular economies, reduce waste, and provide affordable materials for innovation.

II. MATERIALS AND METHODS

A. 3D printing technology and materials

3D printing is an additive manufacturing technology, meaning that products are fabricated through the successive addition of material. Several different 3D printing technologies exist, including stereo-lithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM). Among these, FDM is the most widely used method. This technique employs thermoplastic polymers or other heat-meltable materials to build objects layer by layer. The thermoplastic filaments are supplied from a spool, which is placed in the printer's material feeder. The build platform, on which the model is formed, is typically heated in order to prevent deformation during the process.

The extruder precisely regulates the flow of the filament, which is heated by the hot end to a defined temperature. Subsequently, the nozzle deposits material in successive layers, gradually constructing the model. The advantages of FDM technology include its relatively low cost, the wide variety of filament types and colors available, and the ease of maintenance and operation of FDM printers. However, as with many other technologies, there are disadvantages as well. The most noticeable drawbacks appear on the printed objects themselves: visible layer lines and, in general, lower dimensional accuracy compared to other 3D printing methods.

3D printing therefore represents one of the most revolutionary advances in modern manufacturing. It enables the precise fabrication of products that would be impossible—or at least extremely difficult—to produce using conventional manufacturing techniques. For this reason, additive manufacturing is particularly suitable for prototyping as well as for the production of specialized assemblies [7].

The three most commonly utilized materials in additive manufacturing are PLA, ABS, and PET, with PLA being the most prevalent. PLA is widely adopted due to its excellent printability and because, in general, the final products meet end-user requirements when used as low-stress structural components or simple decorative objects. ABS, by contrast, exhibits higher mechanical strength and greater resistance to both physical and chemical effects than PLA; however, its vapors and emissions may pose health risks during processing. PET is more challenging to handle in printing, while its glycol-modified variant, PETG, readily absorbs moisture from the atmosphere. Nevertheless, both PET and PETG demonstrate superior toughness and durability compared to PLA and ABS.

An older, less accurate 3D printer can be repurposed to recycle discarded PET bottles into PET-based filament, thereby meeting both environmental and economic considerations. The PET bottles must first be heated to achieve a uniform surface, and their bases must be removed, as these cannot be processed by the machine. The bottle is then mounted onto a shaft, with its cut base placed into the machine's cutting section, which performs the slicing

operation continuously (this stage is not automated) [8][9][10].

The resulting plastic strip is fed through the 3D printer's extruder, which has been preheated via the printer's software. During heating, the extruder head compresses the plastic strip into a tubular shape, thereby forming the filament strand. The strand is manually guided to the spool, where it is secured before the motor is switched to automatic winding mode. At the end of the process, the material collected on the spool is ready for use as recycled filament. The embedded systems regulate the whole faultless process [11][12].

B. Filament production

The filament production device converted from a Creality Ender 3 printer was designed to contribute to a cleaner future while simultaneously providing practical benefits to its user. Using a set of bearings, the machine gradually slices a PET bottle—mounted onto a long threaded rod—into a continuous strip. This strip is then processed by the Ender 3 heating head, which reshapes it into a circular cross-section. The resulting filament is collected on a spool mounted on the large gear shaft located on the opposite side of the machine, after being fixed in place. From this point onward, the process becomes automated. However, once the system reaches the narrower neck region of the bottle, the machine must be stopped, as it is unable to handle excessively tapered feedstock [13].

Structurally, the device consists primarily of 3D-printed plastic components, including many parts and coverings, in addition to original 3D printer elements such as metal frames, wiring, circuitry, a motherboard, and functional units like the heating system and the custom-designed cutting mechanism, which is adapted from a ball bearing assembly. Because the raw material consists of discarded PET bottles, it must be thoroughly cleaned before use. Moreover, a thermal treatment (e.g., with a hot air blower) is required to smooth the surface of the bottles. This ensures that the cutting device can operate effectively and without obstruction. As the PET strip passes through the heating nozzle, it adopts the shape of the extruder tip. Instead of forming a solid circular filament, it takes on a hollow, ring-shaped cross-section. This output is then fixed to the spool, enabling the automated winding process to continue until the material is depleted [14].

During filament collection, special attention must be given to the mechanical properties of PET. As a tough and highly durable material, PET stores energy when wound onto the spool. Once tension is released, it behaves similarly to a compressed spring suddenly released, which requires careful handling during subsequent processing. After spooling, however, the filament is ready for reuse and can be employed in 3D printing applications [15].

III. RESULTS

A. The process and programming

The main stages of filament production are as follows: preparation of the raw material, fixation of the raw material, cutting of the raw material, melting and extrusion of the raw material through the heating head, shaping of the raw material into the final product, winding of the finished product onto the reel, and automation of the process via the Ender-3 controller. For stabilizing the PET bottle, the bottle must be supported from at least three directions using a stand-based support system. Since a screw runs through the interior of the bottle, it is logical to utilize this feature to secure its position. However,

because the screw used as the fixing column does not fully match the diameter of the bottle neck, the bottle may still “wobble” at this point during automated operation.

The structural cutting of the raw material is performed by two opposing ball bearings with sharpened edges. These bearings must have sufficient clearance and minimal friction so that the rotation of one induces the rotation of the other without obstruction. The spools were actuated using a LEGO Mindstorms EV3 robot. Figure 5 shows the structure of the cutting device.

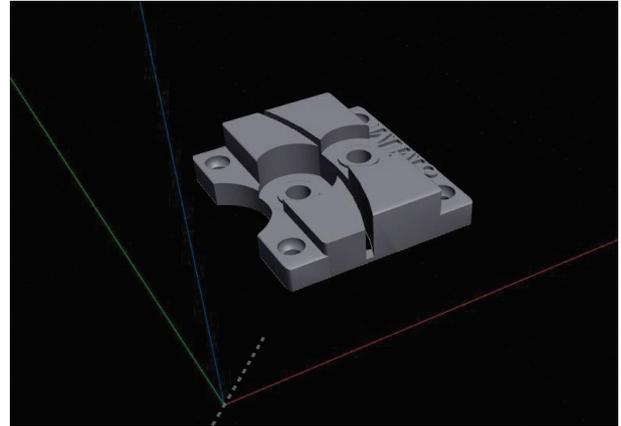


Fig. 5. Rolling bearing housing of the cutting device

Both the feed spool and the take-up spool, driven by the LEGO motors, must be controlled simultaneously to ensure the material passes through the extruder at the correct speed. In selecting the material for the spools and their holders, load capacity and low-friction properties are critical, since a motor is responsible for their drive, and the reels must rotate smoothly. These requirements are fulfilled by the plastic used in the recycling apparatus. In terms of positioning, the spools must be located in the same plane as the cutting mechanism, because the subsequent stage of the process involves a guiding element—a type of “gate” that aligns the plastic filament favorably for the heating head.

The driving motor is positioned next to the reel holder. As the motor shaft directly drives the spool, the motor must be suspended (“in the air”) and fixed in place. This is achieved by aligning the central axis of the motor gear wheel with the cross-shaped axis of the feed spool. The motor need not be rigidly fixed to the machine frame; however, if operational forces require, the motor housing can be supported with vertical structural elements integrated into its mounting sockets. Figure 6 shows the recycling machine.



Fig. 6. The filament production process from PET bottle

In addition, a second motor must be mounted for the collection spool. Unlike the feed spool, this axis is not directly driven by the motor, but instead through a system of gear reductions, with the motor secured to the frame. The principle of operation is thus analogous to the feed spool mechanism. To determine motor speeds, the filament feed rate through the extruder must be known. This parameter is available from the G-code of the 3D printer that serves as the basis for the recycling machine. The specified feed rate is F300, i.e., 300 mm/min. With a reel diameter of 5.2 mm, the corresponding spool rotation speed is calculated to be 1.08853 revolutions per minute (r/min). Figure 7 describes the LEGO motor programming.

```

#include <stdio.h>
#include "ev3.h"
#include "ev3_port.h"
#include "ev3_dc.h"

int main( void )
{
    char s[256], name_port[ 16 ];
    int i;
    uint8_t sn1, sn2, an_port;
    uint8_t port1 = OUTPUT_B; // Port for the first motor
    uint8_t port2 = OUTPUT_C; // Port for the second motor
    bool running = true; // Flag to indicate whether motors should continue running
    if ( ev3_init() < 1 ) return ( 1 );
    ev3_port_init();

    // Initialize first motor
    an_port = ev3_search_port( port1, EXT_PORT_NONE );
    set_port_mode( inx( an_port, OUTPUT_DC_MOTOR );
    ev3_dc_init();

    // Initialize second motor
    an_port = ev3_search_port( port2, EXT_PORT_NONE );
    set_port_mode( inx( an_port, OUTPUT_DC_MOTOR );

    // Find first motor
    if ( ev3_search_dc( plugged( in( port1, EXT_PORT_NONE ), &sn1, 0 ) )
        set_dc_duty_cycle( sp( sn1, 1 ); //Setting duty cycle to 1%
        set_dc_ramp_up( sp( sn1, 2000 );
        set_dc_stop_action( inx( sn1, DC_COAST );
        set_dc_command( inx( sn1, DC_RUN_FOREVER );
    } else {
        //First DC motor is NOT found
    }

    // Find second motor
    if ( ev3_search_dc( plugged( in( port2, EXT_PORT_NONE ), &sn2, 0 ) )
        set_dc_duty_cycle( sp( sn2, 17 ); //Setting duty cycle to 17%
        set_dc_ramp_up( sp( sn2, 2000 );
        set_dc_stop_action( inx( sn2, DC_COAST );
        set_dc_command( inx( sn2, DC_RUN_FOREVER );
    } else {
        //Second DC motor is NOT found
    }

    // Run motors until stopped
    while( running ) {
        // If a button is pressed, stop the motors
        if ( brick_button_pressed( BUTTON_ID_ENTER ) ) {
            running = false; // Set the flag to false to exit the loop
        }

        // Sleep for a short interval before checking again
        Sleep( 100 ); // Sleep for 100 milliseconds
    }

    // Stop first motor
    if ( ev3_search_dc( plugged( in( port1, EXT_PORT_NONE ), &sn1, 0 ) )
        set_dc_command( inx( sn1, DC_STOP );
    }

    // Stop second motor
    if ( ev3_search_dc( plugged( in( port2, EXT_PORT_NONE ), &sn2, 0 ) )
        set_dc_command( inx( sn2, DC_STOP );
    }

    // Reset port modes
    set_port_mode( inx( an_port, OUTPUT_AUTO );

    // Uninitialize the ev3dev-c library
    ev3_uninit();

    return ( 0 );
}

```

Fig. 7. LEGO Mindstorms EV3 robot programme

The larger LEGO Mindstorms EV3 motor is capable of operating at 160–170 r/min. Therefore, a reduction must be applied to the feed spool drive. Since 1% of the nominal motor speed approximates the desired value, a theoretical reduction of 34.5% would be required. However, such a reduction is not feasible with the EV3 motor and software. Moreover, the effect of this discrepancy on the heating process has not been verified; thus, for simplicity, a 1% operating value was assumed in calculations. The second (take-up) spool is directly

connected to the largest gear of the assembly. This gear has 120 teeth and engages a 12-tooth gear, which in turn drives a 30-tooth gear connected to another 12-tooth gear.

Consequently, when the first gear rotates once, the second rotates ten times, and the third twenty-five times. From this ratio, the motor speed required is calculated to be 27.213 r/min. The theoretical maximum speed of the EV3 motor is approximately 165 r/min. From this, the necessary reduction ratio for proper synchronization with the extruder is computed as 16.4929%. Since the EV3 software cannot process fractional percentages, this value was rounded to 17% in accordance with rounding conventions, and applied to the control of the take-up spool motor.

B. Financial aspects

Total cost of energy consumption and filament for in-house 3D printing is about 34,000 HUF. Printing and delivery by a company is about 90,000 HUF. Since the cost of electricity is practically negligible, the overall expenses are primarily determined by the amount of raw material used, calculated on the basis of base prices without considering discounts. The material cost was estimated for 1.5 kg of ABS filament, commonly used in FDM printers, by multiplying the total mass by its unit price per gram. From this comparison, it can be concluded that in-house production remains significantly more cost-effective; however, the final expenses depend heavily on the source and method of acquiring raw materials for printing.

The calculation was carried out as follows: the total weight of the products was measured at 1425 g, which roughly corresponds to two larger spools of filament, based on prior estimates. It should be noted that some components would ideally require a denser construction material. Furthermore, as emphasized in the previously mentioned video, certain parts could be omitted entirely from production. As a compromise, the total mass of the components was taken as the basis for calculation, without further optimization of the design.

The printing process itself requires approximately 160 hours under standard conditions, but depending on the specific printer, this duration may reach 170 hours. Consequently, a consensus-based average of 168 hours was adopted for the calculations, as it allows for easier numerical processing and visualization. The Ender-3 printer consumes approximately 1.5 kWh over a 12-hour period, which translates to 0.125 kWh per hour. Over 168 hours, this results in an electricity consumption of 21 kWh. More effective energy supply can be arranged by using reliable off-grid systems [16].

IV. CONCLUSIONS

Considering that 3D printing itself is still a relatively new technology, the range of accessories and auxiliary tools associated with it is not particularly extensive. In the context of filament recycling, we mostly encounter designs and machines that aim to reuse already manufactured work pieces or defective prints; in other words, they continue to process the same materials with which they have already been working.

However, the recycling of PET bottles within the field of 3D printing is an area pursued by far fewer researchers or hobbyists. Sources in Hungarian on this topic are scarce and often difficult to find, while foreign-language sources generally refer to a single design and device — The Recreator 3D — which is a modification built upon the Ender 3 3D

printer. Consequently, my subsequent work was also based on this system.

Following the introduction of The Recreator 3D, the construction costs of the device were examined with an initial hypothesis, finding that these costs remained largely unchanged. The primary variable influencing overall expenses is therefore the individual builder and their level of expertise.

Designing a cap mechanism that applies downward pressure on the feedstock material while keeping it in position was successful, also exploring the possibility of enclosing the raw material within a quasi-frame. Through the study of 3D models and program code, and by mathematically verifying theoretical implementations a new drive mechanism for the material collection and feed spools of the device using the large motors from the Lego Mindstorms EV3 system were developed.

In conclusion, the paper returns to the initial thoughts, namely that “There is no Planet B.” We must protect the environment that has been entrusted to us, and each of us must contribute using the tools at our disposal — whether through selective waste collection, the use of public transportation, or, for instance, the recycling of PET bottles.

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Simulation and Semantic Description of a Mobile Manipulator

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Abstract—The design and implementation of robotic systems have increasingly shifted toward software-centric development, where simulation plays a central role in the validation and integration of the system. State-of-the-art simulators such as Gazebo and NVIDIA Isaac Sim support rapid prototyping, but primarily emphasize geometric, physical, and visual modeling. Meanwhile, modern robotic systems have become highly interdisciplinary—requiring the consistent integration of mechanical, control, communication, and software layers. This paper introduces a hypergraph-based ontological description framework that unifies these heterogeneous aspects within a single, modular representation. The proposed model leverages the mathematical formalism of directed hypergraphs to capture many-to-many relationships among components, supporting scalable and interoperable robot design. A case study demonstrates the construction of a mobile-manipulator robot, including its corresponding Gazebo simulation and ROS configuration files. Future work will extend the framework toward multi-robot systems and deeper software-level abstractions, enabling greater reusability and semantic consistency across simulation, deployment, and control environments.

Index Terms—mobile manipulator, hypergraph, domain modeling, simulation

I. INTRODUCTION

Modern robotic design relies heavily on accurate kinematic and physical descriptions, which together define the structural and dynamic characteristics of robotic systems. These descriptions serve multiple purposes throughout the design and implementation workflow:

- verifying the kinematic structure and visual appearance of the robot,
- loading the model into simulation environments for visualization and performance evaluation,
- providing a mock-up for software development and system integration, and

- supporting control experiments, such as reinforcement learning or behavior optimization.

Simulation toolkits typically require a well-defined physical description for visualization and basic analysis. However, deeper system integration also depends on detailed representations of sensors, actuators, and their interfaces, including communication links, parameter configurations, and calibration data. Existing description formats—such as URDF [1], SDF, MuJoCo [2], and OpenUSD—often handle interface information separately from the kinematic and physical structure. While this separation is practical for inclusion in simulators like Gazebo [3], it can lead to fragmentation when deploying or synchronizing configurations within complex systems such as those built on the Robot Operating System (ROS).

To address this issue, the present paper introduces a domain modeling methodology based on directed hypergraphs, capable of representing the intricate many-to-many relationships between interface and physical components within robotic systems. Building on prior work in hypergraph-based kinematic modeling [4], this study extends the framework to support the automatic generation of configuration files for ROS 2 and Gazebo, providing a more unified and semantically consistent approach to robotic system description.

II. RELATED WORK

This study focuses on the automated generation of configuration and description files for widely used robotic simulators, with particular emphasis on Gazebo [3]. Gazebo is among the most prevalent simulation environments in robotics and is tightly integrated with the Robot Operating System (ROS) [5]. It enables the creation of comprehensive mock-ups of

robots—including sensors, actuators, and control interfaces—thereby facilitating software development, testing, and system configuration. Other notable simulation frameworks, such as MuJoCo [2] and PyBullet [6], focus primarily on the accurate modeling of the robot’s physical structure and its surrounding environment.

Regarding robot description formats, most simulators rely on URDF [1] or SDF, while MuJoCo employs its own XML-based schema. These formats are primarily designed to represent:

- the kinematic structure of the robot using a hierarchical tree-based approach,
- the visual appearance and collision geometry,
- inertial and dynamic parameters, and
- the spatial placement of sensors and actuators.

However, these schemas do not explicitly capture the interfaces and configurations of sensors and actuators, despite their strong coupling with the physical and control structures of the robot. Such details typically require additional configuration layers or external files for complete system specification.

The approach presented in this paper builds upon the HyMeKo framework [4], [7]—a hypergraph-based description language developed by the authors for modeling complex, multi-relational systems such as kinematic structures and communication networks. By extending HyMeKo, this work aims to provide a unified, semantically rich representation that bridges the gap between physical modeling, interface description, and simulator configuration.

III. METHODOLOGY

The proposed framework provides a unified representation for describing kinematic structures together with sensor–actuator interfaces and their associated control parameters. This work continues the project introduced in [8], extending it with a formal domain model built on the HyMeKo framework. The final purpose is to describe a two arm four-wheeled mobile manipulator, together with a proper communication graph definition and associated sensors (e.g., cameras, laser scanners) and flexibly generate to the target frameworks using simple programmatic queries (e.g., based in Python). Using HyMeKo’s directed hypergraph formalism, the proposed description can express several relationships within a robotic configuration that traditional formats such as URDF cannot explicitly capture:

- connections between sensors and their corresponding information interfaces (e.g., ROS topics), including parametric attributes such as image resolution and their association with physical nodes (kinematic links),
- mappings between control interfaces, control parameters, and actuators,

- associations between communication-graph elements and their physical counterparts, and
- specification of crane-like or branched kinematic structures through fixation points defined on shared rigid bodies.

Overall, the HyMeKo-based description extends conventional robotic models by introducing the following additional elements:

- sensor configurations and their attachment to physical components,
- controller and actuator constraints, including control methods (e.g., position or velocity feedback),
- control-specific configuration parameters (e.g., controller tuning coefficients, refresh rate, monitor rate), and
- communication-graph associations (e.g., ROS 2 topics linked to sensors or controllers).

An excerpt of a six-degree-of-freedom (6-DOF) robotic arm description is shown in Listing 1. This code section defines the state publisher, control method (position or velocity), and control type (trajectory planner) together with the necessary configuration parameters. A complementary example in Listing 2 demonstrates the description of the sensor setup of a four-wheel robot, including camera parameters, spatial placement on the corresponding kinematic link, and the associated communication-graph topics.

Listing 1. Code snippet describing the robot control parameters and state publishers in a 6-DOF robotic arm

```
...
@sim_control_plugin: kinematics.sim_plugin {
  plugin
    "gz_ros2_control::GazeboSimROS2ControlPlugin",
  filename "gz_ros2_control-system",
  parameters "control.yaml"
}
@joint_state_broadcaster:
  kinematics.control_definition {
    - robot.anthropomorphic_arm_control,
    + sensors.joint_state_broadcaster
  }
joint_trajectory_controller:
  controllers.joint_trajectory_controller {
    state_publish_rate 100.0
    action_monitor_rate 20.0
    @interfaces {
      + control_attributes.position,
      - control_attributes.position,
      - control_attributes.velocity
    }
    @joints {
      ->j0, ->j1, ->j2, ->j3,
      ->j4, ->jtool
    }
  }
...

```

Listing 2. Code snippet describing a camera sensor associated with a 4-wheel robot

```
@camera_topic: communication.topic {
  - camera_image_topic_definition,
  - camera_info_topic_definition,
  + camera
}
@camera_connection:
  kinematics.sensors.sensor_connection {
    - camera,
    + camera_link
  }
```

A. Generation of Description Files

The general process for generating configuration and description files from a single hypergraph-based model is illustrated in Figure 1. The framework transforms a unified robot description into multiple target formats (e.g., URDF, ROS 2, and Gazebo configuration files) through a sequence of well-defined steps:

- 1) Robot description: the base model contains the kinematic structure and the communication-graph mappings of the middleware system.
- 2) Design parameters: geometric and configuration parameters (e.g., dimensions, mass properties) that can be injected into the model during generation.
- 3) Hypergraph queries: a set of mapping rules that link elements of the hypergraph-based description to textual representations in the output files. For example, a query may map kinematic links to XML nodes in the generated URDF. These queries are typically implemented as Python code snippets executed in a visitor- or parse-tree fashion over the input model.
- 4) Hypergraph transformation: the queries and textual templates are combined to produce outputs conforming to the target schema:
 - URDF files provide the kinematic and physical description of the robot.
 - The Gazebo configuration and launch files define the setup for simulation and visualization.
 - The ROS 2 configuration files specify the controller parameters and initialize the communication graph for the initialization of the node.

This approach draws inspiration from the Model-Driven Software Development (MDSD) paradigm [9], where system specifications are defined at a higher level of abstraction and transformed into concrete implementation artifacts through automated model transformations.

IV. RESULTS

Using the proposed framework, the individual components of an autonomous mobile-manipulator were successfully modeled and generated:

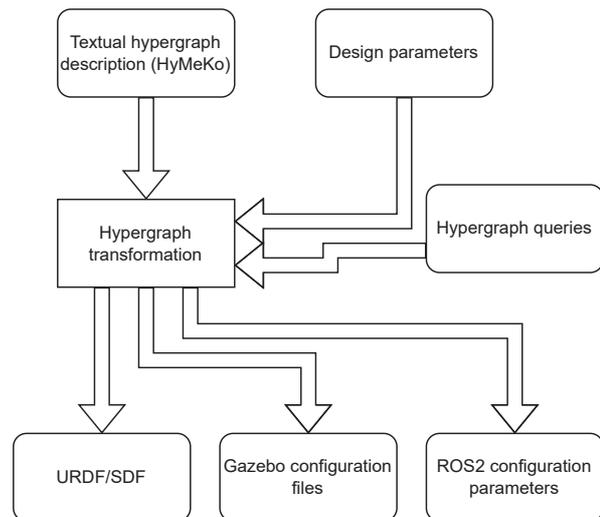


Fig. 1. Overview of the generation process. The framework produces simulation and configuration files from a unified hypergraph-based robot description and associated query templates.

- Robotic arms: two independent 6-DOF manipulators were defined (see Figure 2), each equipped with properly configured control interfaces based on the ROS 2 Control framework [10].
- Mobile base: a four-wheeled differential-drive platform was described, including sensor definitions and control interfaces required for navigation and motion control (see Figure 3).

All components were generated with complete configuration files, including:

- kinematic and transformation trees (for joint state publishers and TF management),
- controller interfaces (with update and monitor rates), and
- sensor configurations (e.g., refresh rates and ROS topic definitions).

Both systems are fully operational within the Gazebo environment and can be controlled via ROS 2 topics and custom control programs. The HyMeKo-based robot descriptions and source code of the language framework are publicly available at ¹. Due to space limitations, the full robot descriptions are not included in this paper.

V. CONCLUSION

This paper introduced a hypergraph-based methodology for generating unified robot description and configuration files compatible with Gazebo and ROS 2. The proposed framework integrates kinematic, control, and sensor-actuator interface descriptions within a single

¹https://github.com/kyberszitty/himeko_lang

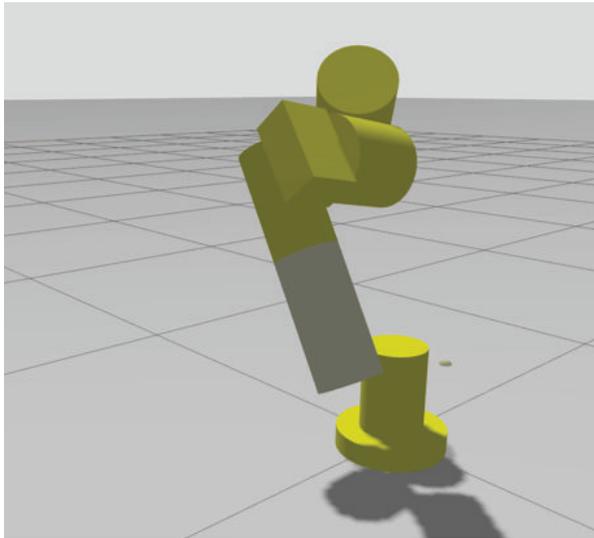


Fig. 2. 6-DOF robotic arm generated from the HyMeKo framework, running in Gazebo with ROS 2 control interfaces and defined communication graph.

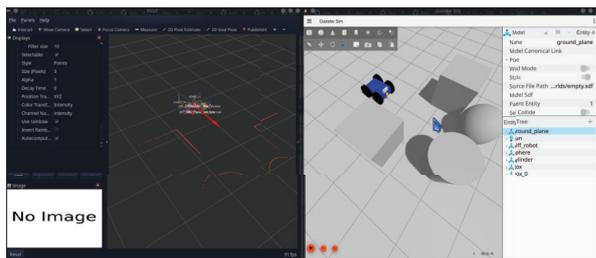


Fig. 3. Four-wheeled mobile robot in Gazebo and RViz, visualizing the configured sensors and real-time environment representation.

formal model, enabling the automatic generation of simulator-ready artifacts.

The approach was validated through the implementation of an autonomous mobile-manipulator, whose major subsystems—robotic arms, mobile base, and sensor configurations—were successfully simulated in Gazebo using ROS 2 control interfaces. While the current results demonstrate the feasibility and consistency of the framework, the complete robot integration and full simulation workflow remain under development.

Future work will focus on quantitative evaluation of the generated configurations, including timing performance, communication latency, and controller stability. In the long term, the framework aims to support the construction of a physical prototype, establishing a seamless bridge between simulation and real-world deployment and further advancing model-driven robot design.

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SESSIONS IV.

Enterprise and Economics

Analysis of a Quality Issues in a Security Access Control System Using the 8 D Method

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Abstract— Consistent product and service quality is a crucial factor for optimizing organizational performance and maintaining a competitive market advantage. The literature on quality management systems and quality assurance practices offers a wide spectrum of solutions to achieve measurable and improvable quality parameters. Practical process analyses highlight the necessity of systematically applying proactive error prevention and reactive troubleshooting methods. This research investigates the significance of two widely adopted quality improvement techniques: the 8D (Eight Disciplines) and FMEA (Failure Mode and Effects Analysis) methodologies. Through a specific case study, it demonstrates the systematic, step-by-step implementation of the 8D technique, illustrating the structured process of fault discovery, root cause identification, and the introduction of lasting corrective actions.

Keywords—8D Methodology, FMEA, Quality Management

I. INTRODUCTION

In today's industrial environment, maintaining high product and service quality is essential for companies that want to stay competitive and meet customer expectations. To support this, many quality improvement systems have been developed, including lean methods, Six Sigma, and various problem-solving techniques. These systems help organizations prevent errors, solve problems efficiently, and improve their processes over time. Among the many available tools, the FMEA (Failure Mode and Effects Analysis) and the 8D (Eight Disciplines) method are two widely used approaches. FMEA is mainly used to identify and assess risks before failures happen, making it a proactive tool. The 8D method, on the other hand, is a structured way to investigate and solve problems that have already occurred. It focuses on finding the root cause and implementing long-term corrective actions. These two methods are often used together, as they complement each other well: FMEA helps prevent issues, while 8D helps resolve them.

This paper presents a case study from the field of security access control systems, where recurring failures required a detailed investigation. The goal of the research is to show how the combined use of FMEA and the 8D method can help identify the causes of quality problems, reduce the cost of poor quality, and support continuous improvement. The methods were chosen because they are well-established in industry, easy to apply in practice, and effective in both risk management and problem-solving. By placing them within the broader framework of quality improvement systems, the study aims to highlight their role and usefulness in real-world applications.

II. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

The Failure Mode and Effects Analysis (FMEA) is a quality management methodology that falls within the domain of failure analysis techniques. The fundamental principle of FMEA is a systematic, step-by-step approach to identifying potential weaknesses or bottlenecks before they manifest. The methodology can also be effectively applied to analyze existing processes or products [1].

An FMEA analysis is typically conducted by a cross-functional team comprised of individuals from different departments within an organization. The team's objective is to assess critical points and the probability of a failure occurring. They define specific criteria and score potential failure modes, from which they derive metrics suitable for risk prioritization. Two key metrics are commonly utilized. The first is the Criticality Number (CN), which is the product of a failure mode's probability, the proportion of defective units, and the operating time. This metric is generally applied to high-risk processes and products. The second metric, used for consumer goods, is the Risk Priority Number (RPN), a product of three distinct factors: Occurrence, Severity, and Detection [2].

The application of the FMEA method commences with the definition of process steps. The second step involves identifying potential failure modes, mapping the problem, and describing its form. The third step is to analyze the failure effects, examining the consequences of a problem's occurrence. This is where the first metric, Severity, is typically determined, assessing the criticality of the consequences. In the fourth step, the possible causes are analyzed using the Occurrence metric, which measures the frequency and likelihood of a given problem or defect. The fifth and final analysis stage is the Detection process, which investigates the presence of adequate preventive or control measures. The product of these three metrics, Severity, Occurrence, and Detection, which are typically scored on a 1-10 scale, yields the RPN. FMEA has several main types depending on the application area and objective, including design, process, service, or system FMEA [3].

While FMEA offers numerous advantages, such as its illustrative nature and broad applicability, it also presents certain limitations:

- The assessment is subjective, as the choice of the failure to be analyzed is determined by the person conducting the measurement.

- It can be superficial.
- Its function is often narrowly confined to meeting customer expectations.
- The individual metrics are typically not examined separately.
- It is time-consuming and may not be suitable for complex systems [2], [3].

III. THE 8D TECHNIQUE

The Eight Disciplines (8D) problem-solving methodology is a structured approach designed to facilitate the identification of a problem's root cause. It comprises eight discrete steps aimed at addressing the fundamental etiology of an issue, moving beyond mere symptomatic treatment. The efficacy of the 8D method is often enhanced through synergistic application with the FMEA (Failure Mode and Effects Analysis) methodology, a practice well-supported in the literature [4].

Originating in military contexts, the 8D technique was subsequently adopted by the automotive industry, a developmental trajectory common to numerous technical innovations [5]. Empirical evidence from multiple researchers confirms its effectiveness, underscoring its value in leading to the implementation of corrective actions that demonstrably enhance product or service quality [6], [7], [8]. The systematic nature of the process necessitates meticulous documentation to provide a comprehensive record of the investigation's progression and its outcomes. This procedure is recognized for its comprehensive scope, integrating various analytical tools and management methods such as the Ishikawa diagram, the 5 Whys technique, Pareto analysis, and other graphical representations like histograms [9]. Researchers have delineated the following sequential process for the 8D technique, distinguishing it from other problem-solving methodologies [9], [10]:

- 1D Form the Team. Assemble a cross-functional team of individuals who are involved in various stages of the process or product and possess relevant information. The team is also responsible for preparing accurate documentation of the data. The team is led by a facilitator or moderator who is independent of the product, service, or system being investigated.
- 2D Describe the Problem. Clearly define and identify the problem, gathering all relevant information. This includes determining the nature and location of the fault, as well as its duration and whether it is a recurring issue.
- 3D Implement and Verify Interim Containment Actions. The objective of this initial intervention is to isolate the source of the error to minimize losses while the problem and its root cause are being investigated. Corrective actions may include holding and re-inspecting products at both the manufacturer's and customer's sites.
- 4D Identify and Verify Root Causes. Investigate the causes that led to the deficiency or problem. This step involves identifying the root cause of all potential failures, using tools such as measurement, testing, the Ishikawa diagram, and brainstorming.

- 5D Choose and Verify Permanent Corrective Actions (PCAs). Develop and recommend a corrective action plan to the team's leader. This step is essentially about creating an action plan.
- 6D Implement and Validate PCAs. Execute the recommended actions and measure their effectiveness. The goal is to eliminate or reduce the likelihood of similar problems occurring in the future.
- 7D Prevent Recurrence. This involves feedback and examining how the implemented actions have contributed to improving the quality of the process or product. It includes measuring and analyzing the success of the corrective actions.
- 8D Congratulate the Team. Conclude the process by drawing conclusions and acknowledging the team's work. This involves evaluating their performance and strengths to motivate them, as well as analyzing the efforts made.

Harazin's study [5] posits a conceptual linkage between the eight stages of the 8D process and the Deming Cycle's Plan-Do-Check-Act (PDCA) principle. Within this framework, the "Plan" stage encompasses the first three steps of the 8D process, preceded by a preparatory Step 0 for problem sensing and identification. The "Do" stage correlates with 8D Steps 4 through 6. The "Check" phase is represented by the 7th step, while the "Act" stage corresponds to the final 8th step, which involves formal closure, drawing conclusions, and acknowledging team achievements. It is notable that Harazin's analysis deviates from other scholarly works regarding the integration of quality assurance tools; for instance, he proposes the application of the FMEA methodology during the 7th step [5].

IV. THE RELATIONSHIP BETWEEN FMEA AND 8D

Research by Koncz [9] further explores the interrelationship between the two methodologies, suggesting that issues identified via the 8D method can be leveraged to enhance FMEA, thereby assisting in the determination of appropriate actions. Krajnc and Trata [11] similarly emphasize the necessity of analyzing, during Step 5, how a customer complaint mandates modifications to existing documentation. The 8D method's standardized steps are widely adopted within the automotive industry, and its application is initiated following the identification of a fault. The shared objective of both FMEA and 8D is the identification and elimination of a failure's root cause. The effective implementation of these methodologies can establish a robust foundation for a quality management system. FMEA serves to prioritize risks; while it does not mandate action for low-level risks, practical experience indicates that this is often considered unacceptable by customers. If an analysis determines a fault or problem to be a critical risk, the product or service must undergo alteration or modification [12].

Scholarly consensus consistently underscores the interdependence of these two methods. FMEA typically functions as a static document that reflects relevant corrective actions from the user's perspective, whereas 8D is primarily engineered to prevent the recurrence of a fault or problem. Following the completion of an 8D analysis, the FMEA is qualitatively supported and updated [13], [14].

FMEA is, in fact, frequently regarded as the most significant management method integrated within the 8D problem-solving process itself [9]. A fundamental requirement for the effective implementation of both methodologies is the formation of a heterogeneous, multidisciplinary, and cross-functional team. Such a team, comprising employees from various departments and functions, ensures a multifaceted and comprehensive analysis, thereby enhancing the probability of acquiring relevant and accurate information [15].

Feature	FMEA	8D
Primary Goal	Proactive Identification & Risk Assessment	Reactive Analysis & Root Cause Elimination
Application Phase	Proactive (Design/Process Phase)	Reactive (After Failure Occurs)
Core Process	Identifies Failure Modes, Effects, Causes; RPN Calculation	8Disciplines: Containment (D3), Root Cause Analysis (D4), Corrective Actions (D5)
Primary Tools	RPN Calculation, Risk Matrix	Ishikawa, 5 Whys, Pareto Analysis
Key Advantage	Proactive Risk Reduction, System Robustness	Root Cause Discovery, Sustainable Solutions
Limitation	Subjective Rating, Time-Consuming	Retroactive Use Only, Documentation Intensive
Interrelation	Updated based on 8D Results	Guides Preventive Actions in 8D (D7)

Fig. 1. FMEA and 8D Method Comparison

V. THE CASE STUDY: APPLYING THE 8D METHOD TO A PRACTICAL EXAMPLE

The subsequent section details a case study demonstrating the practical application of the 8D methodology within a company that manufactures and distributes security access control systems. This project, designated as A3, involves the analysis and corrective investigation of a problem that occurred within a security access control system using the 8D technique. The investigation was conducted collaboratively with the manufacturer, as both parties had a vested interest in both short-term issue resolution and the initiation of long-term corrective actions. Given that continuous product defects were causing persistent problems, the investigation was executed with the full involvement of all stakeholders and various corporate departments.

A3 Project Summary: Swing speed gates and turnstiles					Status
D1 - Background		D5 - Define Corrective Actions			
Justification	Customer Claims = 23 % of the COPQ (Cost of Poor Quality) in this year, 93% of cases related to turnstiles and speed gates.	Activity	Who	When	Status
Context	Suppliers(Int/EXT)	Find the right settings to increase motor unit life cycle.	Customer Service team	2 Feb	
Priority	High	D6 - Validate Corrective Actions			
Team	Customer Service	Corrective Action	Who	When	Status
D2 - Current State		On-site inspection and adjustment	Supplier team	13 Febr	
Problem Statement	Swing speed gates fault & Full-height turnstiles fault	D7 - Preventative Actions Taken			
Process	Inspection together with supplier & Customer Service	Corrective Action	Who	When	Status
Scale of Problem	All swing speed gates and turnstiles	Additional configuration- technical training for customer service in April.	Supplier technical team	20 April	
D3 - Objectives		D8 - Follow up			
Current State	Last year 21% of the total COPQ	Customer feedback			
Future State	Reduce by 38% - to be checked in comparison to last year				
D4 - Root Cause Analysis					
Motor unit overload because of wide range operation settings					

Fig. 2. Project summary

This figure provides a summary of the analysis process. Subsequently, the documented steps of the A3 project are presented in detail, and their effectiveness is summarized. The background analysis clearly demonstrated an increase in the Cost of Poor Quality (COPQ). This represents the additional costs incurred due to quality problems. Some of these costs are easily quantifiable, such as the cost of repairs, scrap, potential accidents, extra labor hours, energy consumption, or penalties. Other costs are not fully quantifiable and are of a non-monetary nature, such as time expenditures or damage to the company's reputation. The concept of quality is often paired with meeting customer expectations in the literature, which is why it is essential to prevent a drop in quality, as it can lead to customer disappointment and a potential decrease in sales [16], [17].

D1-Background

- Customer buys swing speed gates and full-height turnstiles from the supplier, which are subsequently resold
- Sold: Swing speed gates:41 pcs + full-height turnstiles:6 pcs
- Defective Swing speed gates: 8 pcs + defective full-height turnstiles: 1 pcs
- For products purchased in the last 2 years, the defect swing speed gate rate was 19 % and the defect full-height turnstiles rate was 16 % during the warranty period
- There were a number of costs incurred during the problem investigation period (e.g travel, device replacement, repairs, shipping fee)
- Already this year we have orders for 20 swing speed gates
- The supplier tries to deal with the defects, but for the time being we do not see any improvement in quality

Fig. 3. D1

D1 - Define the Background and Team

In this case, the failure rate for the security access control systems purchased for resale by the company was 19% for the first product type and 16% for the second type during the warranty period. During the problematic period, various costs were incurred, including travel, equipment replacement, repairs, and shipping fees. The supplier promised to address the defects, but initially, no improvement in quality was observed. As mentioned earlier, this is the "0-step" identified in some research, which involves identifying the problem or defect. Considering the complexity, the team was composed of experts from customer service, design, and software development departments.

D2 - Describe the Problem

In this step, the company conducted a brainstorming session to assess the situation. The summary of this assessment can be illustrated by answering the following questions see in Fig.4.

D2-Current State

- Swing speed gates fault & Full-height turnstiles fault



Who is effected?	Customers with delivered speed gates & turnstiles productions Every gate that has been installed so far is potentially affected.
What type of problem is this?	Operating problem (all access types are affected, i.e. security and safety level)
Why is it a problem?	Powerless motor unit -> Difficult to turn the arms
Where was it observed?	Project site
When was it noticed?	Observation spread 2-3 weeks after installation
How did problem occur?	Frequent passage errors, traffic jam
How Often ? YTD	9 pcs claim gates/year

Fig. 4.D2

D3 - Setting Objectives and Corrective Actions

In this phase, the task was to implement initial actions necessary until the source of the problem could be fully identified and resolved. The responsible parties for each task were also defined, along with the costs incurred due to the defective performance and the overall objective.

D3-Objectives

Description	Owner	Status
Containment action – WIP and Stocked finished goods settings correction	Customer	Done
Solving customer issues – adjust the critical settings and parameters	Supplier	Done
Find the right settings to increase motor unit life cycle	Supplier	Done
Optimization the dynamic properties of motor unit:	Supplier	Done
<ul style="list-style-type: none"> Opening speed parameter define Motor unit sensitivity parameter define 	Supplier	Done
Reduction of COPQ cost related to Gates and turntles reduction by 38%	Supplier	Ongoing

Fig. 5.D3

Following the introduction of these initial corrective actions, the goals were achieved by modifying settings and parameters and optimizing the system. The Cost of Poor Quality (COPQ) value is currently being reduced, with further reduction being a continuous objective.

D4 - Root Cause Analysis

The failures occurred during product use, regardless of the operating temperature (inside or outside). In both cases, the motor was found to lose power within 1-2 days. An analysis of the gate's activity by the manufacturer was deemed necessary. The log analysis determined that excessively high parameter values were negatively impacting the motor's performance. Due to the issue, the supplier committed to testing the system, subsequently verified the parameter values, and confirmed that the problem was attributable to the software's operation.

D4-Root Cause Analysis

- The malfunction occurs during use of products
- Independent of the operating temperature (inside or outside) – experienced both cases
- Within 1-2 days the engine lost power
- Manufacturer analysis of logs collected by the gates (supplier action)
- Log analysis found that too high parameter values negatively affect engine performance
- The supplier tests - checked parameter value and confirmed the cause of problem

Observed wrong usage of parameters:

Swing speed gates		
Dynamic properties of motor unit	Value ranges	Value failure
Opening speed	1-9	9
Full-height turnstiles		
Dynamic properties of motor unit	Choice values	Value failure
Braking distance angle	1-120 [degree]	90
Go-call	0-50 [degree]	40
Motor unit sensitivity	1-100	80

Fig. 6.D4

D5 - Defined Corrective Actions

The implementation of corrective actions followed the root cause analysis, which involved a software redesign of the device. These corrective steps were initiated immediately after the root cause was identified.

D5-Defined corrective actions

- Upload new configuration in the application – anytime during turnstile operation
 - New configuration details:

Swing speed gates		
Dynamic properties of motor unit	Value ranges	Value failure
Opening speed	1-9	3
Full-height turnstiles		
Dynamic properties of motor unit	Choice values	Value failure
Braking distance angle	1-120 [degree]	15
Go-call	0-50 [degree]	0
Motor unit sensitivity	1-100	5

- Upload new firmware in the application – anytime during turnstile operation
The details of the new firmware are known only to the manufacturer

Fig. 7.D5

D6 - Validated Corrective Actions

Following the determination of the corrective actions, a checklist was created, jointly compiled and audited by the 8D team members. The table below illustrates the review and implementation of these actions.

D6-Validated corrective actions:

#	Corrective actions	Done
1	On-site inspection and adjustment <ul style="list-style-type: none"> Inspection of correct position of end stops is performed by manual turning of wings to their end positions Function reset – initialization <ul style="list-style-type: none"> reset of internal registers reset of error register activation of device initialization detection of faults 	Y
2	Upload new configuration in the application – anytime during turnstile operation	Y
3	Upload new firmware in the application – anytime during turnstile operation	Y
4	Last year 2 inspections at customer sites with 0 issues found after corrective actions implemented	Y
5	Monitoring trend in the Customer claims database (in TST)	Y

Fig. 8.D6

D7 - Review and Verification of Preventive Actions

After implementing the immediate corrective actions, the team set long-term goals and created a list of preventive processes and measures to be introduced. These were outlined in the following three points.

D7-Preventive actions taken

#	Preventive Actions	Done
1	Additional configuration-technical training for customer service and installers, for better initial configuration of the gates	within 6 months
2	Quality control procedure creation	within 6 months
3	Preventive maintenance done by company – every year revision	within 7 months

Fig. 9.D7

D8 - Monitoring and Team Recognition

As the project concluded, the team members agreed that continuous monitoring of customer feedback was expected. They also scheduled an annual review of the system settings. The final step was to acknowledge the team's work, summarizing their successful collaboration and the project's key outcomes.

D8-Follow-up

- Customer feedback monitoring – stored in TST (Technical Support Tool)
- Settings check annually

Fig. 10. D8

VI. CONCLUSION

The objective of this research was to provide a relevant, comprehensive, and illustrative analysis of the practical application of the 8D problem-solving technique. In accordance with the company's request to preserve confidentiality, all sensitive corporate information has been omitted. The study emphasizes the critical importance of addressing quality issues and investigates the relationships between two widely used quality management techniques: FMEA and 8D. As demonstrated throughout this analysis, these two methods are closely interconnected in practical application. For a complete analysis, the use of other quality management techniques is also recommended and constitutes standard corporate practice.

The project documentation, provided with the support of the distributor, serves to illustrate the utility of the 8D method. The case study successfully demonstrates the method's effectiveness in identifying faults and deficiencies.

It also highlights the efficacy of the investigative process, which culminated in the successful implementation of corrective actions.

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An Overview of Indicators Related to Innovation and Competitiveness

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Abstract - In the 21st century, innovation is becoming one of the most important tools for sustainable economic development, providing a competitive advantage for economic organisations and contributing to the solution of social and environmental challenges. Innovation and competitiveness are closely linked. However, in this study, we did not attempt to provide a complete presentation of the two concepts, as a significant part of the literature analysis has already done so. Our study focuses on understanding the two concepts and making them "tangible" through literature and indicators. We have attempted to review the international innovation and competitiveness indicators created by various organisations. In our changing world, we need indicators that reveal the national and regional aspects of the innovation and competitiveness performance of nations and regions. We have presented this in a short study.

Keywords — innovation, competitiveness, rankings, review, performance.

INTRODUCTION

The topic of competitiveness is constantly present in public conversation, and the average person is coming across it more, whether through political events or economic news. The question may be raised why we come across this concept so often. The phenomenon of competitiveness has already been a topic of interest to researchers for quite some time, namely how economic organisations, national economies or supranational entities can gain a competitive advantage and become more competitive. In the 21st century, innovation is becoming one of the most important tools for sustainable economic development, contributing to increased competitiveness and the resolution of social and environmental challenges through the creation of new value. In Drucker's words, innovation means activities that focus purposefully on achieving change in the economic and social opportunities of a business [1]. Change, when it results in the creation of new value, leads to innovation, which is the main basis for competitiveness. Porter says that companies secure their competitive advantage through innovation, which they need to maintain through continuous development [2]. Varga highlighted the close relationship between innovation and competitiveness, conducting a research study on national economies (in EU member states) based on innovation and competitiveness assessments and analysis by the European Commission and leading competitiveness research centres. He found that the most competitive countries also lead the way in innovation performance [3]. Csath defines competitiveness as follows:

"A national economy is competitive when the nation's capabilities are well utilized and continuously strengthened in the long term, companies create jobs that require as much knowledge and creativity as possible and generate high added value, and as a result, people's standard of living and quality of life continuously improve." [4]. In this definition, the author clearly presents the human aspect, in which, with the proper and supportive functioning of social subsystems, creative individuals contribute to competitiveness. According to Kohnová, the key to increasing the competitiveness of SMEs lies in the quality and agility of the workforce. The flexible attitude of employees is a critical determinant of business success, thus supporting the organisation in following dynamic changes and innovating [5]. In this short study, we will not deal with clarifying the two concepts, as there is a wealth of literature on this subject. Our focus is on understanding the two concepts and making them "tangible" through literature and indicators, and we have examined previous analyses that have focused on this research. We have attempted to review the international innovation and competitiveness indicators created by various organisations. In our changing world, we need indicators that reveal the national and regional aspects of the innovation and competitiveness performance of nations and regions, because their socio-economic dimensions are becoming increasingly important. We have undertaken to present this in a short study.

LITERATURE REVIEW

The authors examined the theoretical framework of interactions between innovation and competitiveness in order to explore the specific characteristics of different industries and business environments. Their study touched upon indicators of innovation performance. They pointed out that one group of experts disputes the validity of the measurement results by criticizing the indicators, while another raises methodological questions (e.g., mixing input and output indicators, weighting, etc.). The authors draw attention to the simplistic nature of innovation measurements and their compensating effect, which can hide the real situation [6].

Among the studies, we find one that also takes into account the history of innovation statistics, the legal background, and the limitations of early innovation statistics [7]. In 2010, the authors focused on approaches to measuring the innovation capacity of regions, concluding that the use of a complex set of indicators may be the appropriate choice. They recommended assessing the

potential of domestic regional databases and new indicators. They highlighted aspects that they recommended for consideration. They believed that corporate innovation results were difficult to capture and considered that the supportive role of economic policy at the micro-regional level should be recognized; they also recommended the use of more indicators describing the economic structure, which had not been available until then [8]. In 2013, Csugány examined data from EU member states and the United States in terms of technological progress. He concluded that the main reason for the weakness of European R&D&I is the role of the European state in catalysing scientific research, while the US relies more on the corporate sector. The author also pointed out that within Europe, Western countries are keeping up with the US, while countries in the Mediterranean and the newly joined countries are not [9]. In 2013, Keresztes examined the possibilities for measuring innovation activities and highlighted, among other things, that the need for continuous development of indicator systems is created by changes in the concept of innovation. He suggested that domestic economic organisations are not aware of the wide range of interpretations of innovation activities, which may lead to inaccuracy in the reports. He also suggested that it would be useful to recommend innovation indicators to companies that are easier to generate in relation to domestic methodologies, which would allow for a more sophisticated measurement of Hungarian innovation performance [10].

Based on interviews with corporate executives conducted in 2017, the author concluded that the "European paradox" phenomenon is also recognisable in Hungary. According to this, despite cutting-edge research being conducted in the EU, the results do not contribute to increasing competitiveness and have little practical impact. He pointed out that there were few innovations that could be included in international innovation surveys because they were simply not patented or not done in Hungary. He said that the most important tasks were to resolve the mistrust between economic organizations and researchers and to balance the differences in innovation attitudes between the two sides. He also said that easily generated innovation indicators should be recommended to companies in order to refine domestic innovation performance [11].

In his study, Borsi concluded that R&D activity in the business sector (in a significant part of EU countries) is less related to the proportion of innovative enterprises, while certain characteristics of the innovation system's functions are increasingly influenced by this. He thus draws attention to the innovation system, its functions and collaborations, through which the dynamism of innovation phenomenon can be better understood. It emphasises that in the age of knowledge-driven economies, it is within this framework that we must seek answers as to how to move forward in terms of a country's innovation performance. It points out that increasing a few selected indicators will not create miracles in this area [12].

In 2018, the authors provided a brief overview of the characteristics of human resource measurement that are essential for technological development. They examined which areas of human resources development could be used to launch technological catching-up in less developed countries, and the transition from imitation-driven growth to innovation-driven growth. They concluded that both quantitative and qualitative measurement are necessary for this [13]. In 2018, the author pointed out the decline in Hungarian innovation performance and referred to the socialist curse affecting post-socialist countries and the reproduction of factors hindering innovation. He also pointed out an example of inconsistency in the methodology of the indicators, which he found in relation to measurable innovation in education. In the case of the "total composite education innovation index 2000–2011," Hungary ranked an impressive 6th. International measurement data (e.g., TIMSS, PIRLS) played a prominent role in the index, in which the country performed well, while PISA, for example, played a minor role, which may have contributed to the good result [14]. In 2018, the author found that there is a deficit in innovation and knowledge in Hungary. He concluded that extending value chains, shifting towards innovative activities, and increasing the number of innovative jobs could help improve competitiveness. In this process, the creation of new value and knowledge produced domestically can play an important role, which can influence our competitiveness and improve our position in the international area. To this purpose, the level of investment in human capital and the efficiency of resource use need to be increased. The author's proposals for change also contribute to increasing budget revenues [15].

In 2020, the author researched methods for measuring innovation systems, summarizing three basic types according to their complexity. The first category includes innovation indicators, the results of which are evaluation tables that allow for the comparison of innovation systems in different countries and regions. In the second type of measurement methods, he mentioned statistical and econometric methods. In the third group, he highlighted the use of simulation methods that capture the complexity of innovation systems [16].

Alhusen and his co-authors proposed a new measurement concept in 2021, introducing a new set of indicators. They recommended this as a complement to the "Doing-Using-Interacting" (DUI) method for describing informal innovative activity and the "Science-Technology-Innovation" (STI) method based on a conscious approach to research and development [17]. The set of indicators (47 in total) provides a record of knowledge flows and the intensity of relevant facilitators across 15 categories. By highlighting the role of individual competitiveness and mentioning the tasks of the state in this area, the author clearly takes a position in support of competition based on knowledge and innovation. Csath presented new elements of the interpretation of competitiveness in his 2024 study (sustainability, resilience, preparedness for the future,

digitalization, and new technologies) and cited the main findings of recent studies by the most well-known competitiveness research organisations. He also focused on the MNB's Competitiveness Report, agreeing with its main findings, such as the shift from a quantity-based to a quality-based approach and the need to increase total national wealth [18]. Náдай analysed the indicators of the European Innovation Scoreboard using Kohonen's self-organising maps method. He emphasised that increasing public R&D expenditure, the number of higher education students and SME innovation could help to influence the country's innovation weaknesses [19]. In his article, Juhász pointed out that changes in the economic performance of a country are not necessarily shown by moves up or down in the rankings [20].

THE ROLE OF INNOVATION IN REGIONAL DEVELOPMENT

D. Santos found that in his case study on the entrepreneurial ecosystem in Coimbra, the activities of incubators and local innovation stakeholders (e.g., science parks) played an important role in improving the city's competitiveness. As a result, university businesses were created (spin-offs, start-ups), the local innovation system became more business-oriented, massive networking began, and a deeper culture of cooperation developed. He emphasized that the spillover effect of new knowledge-based startups is beneficial for the development of local companies. He pointed out the role of urban and regional ecosystem building in improving the competitiveness of urban and regional economies [21]. J. Lopes and his co-authors drew attention to the need for a dominant entrepreneurial and free entrepreneurial culture in Europe, which would help overcome resistance to change and protect established interests. They emphasised that companies should play a greater role in the development of knowledge networks as a contribution to increasing innovation capacity. They concluded that the implementation of the Region Smart Specialisation Strategy (RIS3) has a positive impact on European innovation capacity [22].

Parrilli and his co-authors pointed out the role of regional characteristics when examining regional differences in broader technological patterns. They found that every region in Europe is seeking to move away from its current level of development, so those who are falling behind are trying to catch up. They highlighted that those in the modest innovator category need to improve their efficiency in applying scientific, technological, and innovation drivers, while moderate innovators need to improve their ability to create radical innovations and, at the same time, commercialise their innovations. It was noted that leading innovators and strong innovators can effectively use all drivers to maximum effect [23].

Kadlec and his co-authors pointed out that, based on an analysis of the past 20 years, there is a visible trend of patents being outsourced from less developed regions to regions where multinational companies are headquartered. They also observed how foreign companies exercising control over the national knowledge production of certain economically underdeveloped regions, based on the

outsourcing of patents. This may also point to weaknesses in the business sector that describe less innovative regions. It was highlighted that companies operating in regions characterised by strong basic research may be able to utilise the knowledge thus acquired, which can have a positive impact on the regional economy [24]. In their study, Halásková and her co-author examined NUTS 2 regions in Western Europe to identify groups of innovation performance and their spatial distribution. They found that innovation performance increases over time, but is characterised by regional inequalities, which may be influenced by public and private sector R&D indicators. They highlighted that innovation performance plays the most important role in the competitiveness of countries and regions [25].

ON THE COMPETITIVENESS VISIONS OF EU

The European Union has recognized that it needs a turning point in terms of competitiveness if it wants to maintain its economic and political weight and contribute to maintaining the standard of living of EU citizens. The first step in this process was to face up to the current situation, with Mario Draghi, former president of the European Central Bank, playing a central role in this regard with his report on the subject. The document, presented at the European Parliament's plenary session in September 2024, focused on three key factors through which the EU's competitiveness can be enhanced: Closing the innovation gap; Decarbonizing the economy; Reducing dependencies [26]. After the report was published, its analysis and discussion began in academic circles as well. In relation to the Draghi report, Juhász P. pointed out the lack of literature on the concept of competitiveness at the EU level, as well as the disputable nature of its conclusion based on the competitiveness of EU member states [20]. Ábel and his co-authors highlighted the areas of education, healthcare, and taxation in their study, which did not receive sufficient attention in the report. They drew attention to trends that can be observed in the educational performance of European countries and the health status of the workforce, which predict problems. They emphasised that the quality of human capital is an important condition for the effective functioning of the economy, as are physical infrastructure conditions [27].

In January 2025, the European Commission presented the Competitiveness Compass, which was intended to put the recommendations of the Draghi report into practice. In addition to the three pillars, five further horizontal instruments were identified to boost competitiveness in all sectors: "1. Simplification and the creation of a more favourable business environment by reducing bureaucracy; 2. Removal of remaining barriers in the single market; 3. Ensuring more efficient financing with the products of the savings and investment union; 4. Filling the skills and labour gaps with the skills union; 5. Creating better conditions and implementing EU policies with the competitiveness coordination tool" [28].

After honest reflection, the intentions of EU and the willingness of EU member states to act can help us

move forward in the field of innovation performance, thus contributing to increased competitiveness.

METHOD

We did not focus on clarifying the concepts of innovation and competitiveness, given the rich literature on the subject. Our interest is focused on making the two concepts "tangible" through indicators, and we examined previous analysis that concentrated on this. Our analysis of the literature touched on the role of innovation in regional development, the differences between European regions, and, briefly, the EU's vision of competitiveness. We then attempted to review the international innovation and competitiveness indicators created by various organisations, choosing those that appear regularly in the literature we reviewed.

INTERNATIONAL RANKINGS, REPORTS

Innovation performance has become a key indicator of the competitiveness of countries and regions, and indicator systems are necessary to understand it. The European Union's relevant performance indicators relate to research and innovation. The European Commission's *European Innovation Scoreboard* (EIS, annual) and *Regional Innovation Scoreboard* (biennial) are tools for assessing the innovation performance of the EU and its member states from an international perspective.

EU member states can be classified into four categories based on their performance relative to the EU average: Innovation Leaders (EU average >125%), Strong Innovators (100–125%), Moderate Innovators (70–100%), Emerging Innovators (<70%). In the results for 2025, Hungary can be listed among the emerging, catching-up innovators, as it achieved 69.5% of the EU average, ranking 22nd among EU member states [29].

The *Regional Innovation Scoreboard* allows for a comparison of the research and innovation performance of EU Member States and other European countries at regional level. Budapest ranks 112th among the 244 EU regions, standing out from the seven Hungarian planning and statistical regions with its significant innovation performance, placing it in the moderate innovator category. The other Hungarian regions are in the emerging category. The Central Transdanubia region, where our university faculty is located, ranks 213th overall, placing it fifth among Hungarian regions. It stands out among European regions in a single performance indicator, the "Exports of medium and high technology products" category, in which it ranks second behind Budapest in the regional rankings, outperforming the EU average by 19.3% [30].

EU Member States can also be compared based on the *Eco-Innovation Index*, which measures eco-innovation performance between 2014 and 2024 in five thematic areas: eco-innovation spending, eco-innovation activities, eco-innovation outputs, resource efficiency outcomes, and socio-economic outcomes. The Index highlights a

country's innovation performance in the field of green technology and solution development. In this 2025 ranking, Hungary ranks 26th among EU member states [31].

According to *Hungary's 2025 Digital Decade Country Report*, our country has a very good digital infrastructure, but there is still work to be done in the area of business digitalisation [32]. The report highlights that access to e-health records is above the EU average. According to the report, the use of artificial intelligence is currently falling behind. We touched on the digital country report because of the link between innovation and digitisation.

The World Intellectual Property Organization (WIPO) evaluates global economies in the field of innovation based on their innovation capacity, as measured by the *Global Innovation Index (GII)*, which consists of approximately 80 indicators (grouped according to innovation inputs and outputs) [33]. Hungary currently ranks 36th out of 139 economies in 2025. Among the main findings of the report, it was highlighted that Hungary will perform better in terms of innovation output than innovation expenditure in 2025, with improvements in eight indicators in the short term and declines in three. Hungary currently has no clusters that could appear among the leading innovation clusters in the GII.

The International Institute for Management Development (IMD) World Competitiveness Ranking uses a complex matrix that takes into account political, social, and cultural dimensions to show the competitiveness of economies, with quality of life being an important factor [34]. Hungary ranks 48th in the 2025 ranking, moving up six places compared to 2024, but slipping two places compared to 2023. The report sees one of the challenges for Hungary in 2025 as raising awareness and promoting the potential applications of artificial intelligence in the business sector and society.

The Global Talent Competitiveness Index (GTCI) 2023 report (INSEAD & Portulans Institute) is an EU-accredited index that can serve as a source for understanding global talent competitiveness and as a basis for developing strategies to boost the economy [35]. The 2023 report covers 134 countries, with Hungary ranking 38th. The report predicts what we can expect in the next decade. For cities and regions, it states that it may pave the way for the development of new talent strategies and the emergence of talent-based innovation. If a municipality or geographical region wants to become a talent hub, quality of life and sustainability will be key to attracting talent.

Title	Scope	Indicator areas	Purpose	Methodology - data collection
European Innovation Scoreboard, EIS	Member States of the EU, other European countries and selected third countries	32 indicators, 4 pillars, 12 innovation dimensions. Human resources, Attractive research systems, Digitalisation, Finance and support, Firm investments, Investments in information technologies, Innovators, Linkages, Intellectual assets, Sales and employment impacts, Trade impacts, Resource and labour productivity	Evaluation of the innovation performance of EU Member States in comparison with other European and selected third countries.	quantitative
Regional Innovation Scoreboard, RIS	Regions of EU Member States	The same as EIS, but with results presented at the regional level.	Comparing the innovation performance of regions in EU Member States.	quantitative
Global Innovation Index, GII	Countries of the world (139 in 2025)	78 indicators, 7 pillars. Innovation Input Sub-Index: Institutions, Human capital and research, Infrastructure, Market Sophistication, Business Sophistication. Innovation Output Sub-Index: Knowledge any technology outputs, Creative outputs.	Assessment of innovation performance at national level for comparison at global level.	quantitative and qualitative
Eco-innovation index (EEA EII)	EU Member States	12 indicators, 5 areas. Eco-innovation inputs, Eco-innovation activities, Eco-innovation outputs, Resource efficiency outcomes, Socio-economic outcomes.	Assessing a country's innovation performance in the field of green technology and solution development.	quantitative and qualitative
Hungary 2025 Digital Decade Country Report	EU Member States	16 Digital Decade KPIs, 4 core areas: Digital skills, Digital transformation of businesses, Digital infrastructures, Digitalization of public services.	Evaluate EU member state's progress toward the 2030 Digital Decade targets and identify challenges.	quantitative and qualitative
(IMD) World Competitiveness Ranking	Countries of the world (69 in 2025)	Total criteria: 262, including 170 data indicators and 92 criteria based on a survey of business leaders. Four main pillars: economic performance, government efficiency, business efficiency, and infrastructure.	Establish a basis for comparison and to identify the strengths and weaknesses of economies through the pillars.	quantitative and qualitative
Global Talent Competitiveness Index, GTCI	Countries of the world (134 in 2023)	69 indicators, grouped into 6 pillars and 14 sub-pillars: Enable, Attract, Grow, Retain, Vocational and technical skills, Global Knowledge Skills.	Summary of concepts related to human capital and competitiveness at national level, for the purposes of international comparability.	quantitative and qualitative

TABLE 1: Comparative table of international indicator systems
 Source: edited by the author based on information found on the websites of international indicator systems

The EIS and RIS (based on Eurostat data, among other sources) are closely related. The EII, the index of the European Environment Agency (EEA), examines innovation performance primarily in the field of green technologies and solutions. The GII, the index of WIPO, examines the innovation performance of nations within a global framework. The EIS, RIS, and GII systems have in common that they deal with the role of human capital, R&D, intellectual property, and corporate innovation. The IMD World Competitiveness Ranking examines both hard and soft conditions in its assessment of competitiveness. The Global Talent Competitiveness Index perhaps better reflects the opportunities available for individual development. There are also differences in the data collection of the indicator systems examined, as all except the EIS and RIS (both are only quantitative) use quantitative and qualitative methods.

SUMMARY AND PROPOSALS FOR FURTHER RESEARCH

In our short study, we reviewed the results of studies analysing international indicator systems that focus on the relationship between innovation and competitiveness. We

analysed the literature on the role of innovation in regional development, the differences between European regions, and briefly touched upon the EU's competitiveness concepts. We then reviewed the domestic relevance of international innovation and competitiveness rankings created by various organisations. In our changing world, we need benchmarks and indicators that reveal the national and regional aspects of the innovation and competitiveness performance of nations and regions, as their socio-economic impact is becoming increasingly important. It is necessary to use indicators to understand the current situation so that interventions can be formulated to achieve improvements in areas that are falling behind.

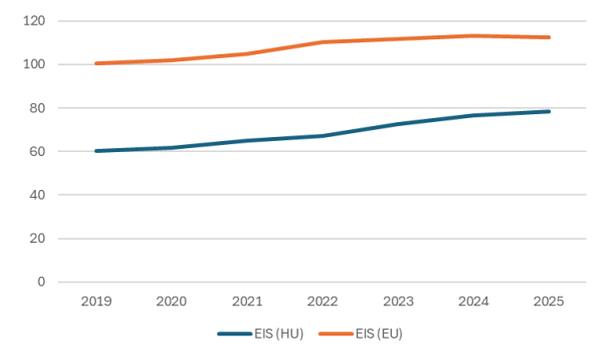


Fig 1: Hungary's EIS index development compared to the EU average 2019-2025

Source: edited by the author based on information found on the websites of EIS (European Commission, 2019-2025)

Hungary's innovation performance shows slight but steady improvement compared to the EU average, according to data from the European Innovation Scoreboard 2019–2025.

The economic strength of a country will be influenced by the readiness of its population and the state of its human capital. In addition to hard infrastructure investments, the government must also pay special attention to the development of soft infrastructure. People are the most important factor in the process of creating innovation.

As we enter the age of AI, we can use artificial intelligence to generate the ideas that can lay the foundation for innovation, but the birth of innovation will require a team of committed people, their belief and their confidence that the process can be completed with the creation of value.

The current research did not attempt to delve deeply into the details of the indicators, but it would be interesting in the future to conduct research comparing and analysing the methodologies of different rankings.

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Motivational Drivers of Women Entrepreneurs

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Abstract— In our study, we analyze the entrepreneurial motivations of women entrepreneurs, with particular emphasis on the internal drivers that go beyond traditional financial objectives. Women entrepreneurs make a significant contribution to economic variety, as they often operate in sectors that differ from those dominated by men. Our research focused on the factors that encourage women to start their own businesses, and on the role played by self-fulfillment, flexible working hours, and the desire to achieve work–life balance.

Applying a quantitative method, we conducted a questionnaire survey in March 2025, which respondents completed online voluntarily and anonymously. A total of 76 active women entrepreneurs filled in the questionnaire. The main hypothesis of our investigation was that self-fulfillment and freedom in time management play a key role in the motivation of women entrepreneurs. Our results show that women entrepreneurs often choose business activities that align with their personal values and life situations, while also providing opportunities to express their creativity.

Our research contributes to a deeper understanding of entrepreneurial types among women and highlights that the motivations of women entrepreneurs are diverse, unique, and often closely intertwined with their personal circumstances and social roles.

Keywords — *entrepreneurial leadership, women entrepreneurs, motivation, self-fulfillment, human resources, human resource management, flexibility*

I. INTRODUCTION

Women are becoming increasingly confident and intentional in starting their own businesses; however, their motivations, challenges, and driving forces often differ from those of men — shaped by their social roles, family responsibilities, and personal goals. This research focuses on examining the entrepreneurial motivations of women, with the aim of exploring the internal and external factors that encourage them to start a business.

The study centers around the following key questions:

- What motivates women to start their own businesses?
- How do these motivations differ across life stages (young entrepreneurs, mothers, older women)?
- How important is flexible working time, and how is it implemented in practice?

The relevance of the topic is underlined by the fact that supporting female entrepreneurship has become a strategic objective both in the European Union and in Hungary. Yet, practical experience shows that women still face more difficulties in accessing information, funding opportunities, or entrepreneurial networks. At the same time, an increasing number of studies emphasize the importance of family background: a supportive environment has a positive impact on entrepreneurial confidence and sustainable operation, while a conflictual family situation can be a hindering factor [1].

This research not only presents the motivations and types of female entrepreneurs but also aims to inspire those who are currently considering starting their own business. Because women — regardless of their life situation — create value.

II. LITERATURE REVIEW

A. Sectoral Distribution of Women-Owned Businesses

Between 2018 and 2022, the proportion of women starting new businesses in Hungary exceeded the EU average. While the female entrepreneurship rate in the European Union stood at 6%, in Hungary it reached 8%, indicating a growing entrepreneurial spirit among women [2].

On a global scale, women entrepreneurs are most active in the *trade sector*, where their presence reaches 48.6%, compared to 40.1% among men. This sector therefore plays a key role in the expansion of women-led enterprises. The second most significant area is the *public, health, education, and social sectors*, where women represent 17.6%, while men account for 10.9%, reflecting women’s increasing engagement in socially oriented fields.

Other important sectors include *financial, professional, and administrative services*, where female entrepreneurs make up 16.4%. In contrast, women’s presence in *manufacturing and transportation* stands at 10.8%, and in the *information technology (IT) sector* it is only 2.3%, compared to 5.3% among men. The latter clearly indicates that there is still significant potential for encouraging female entrepreneurship in the IT field [3].

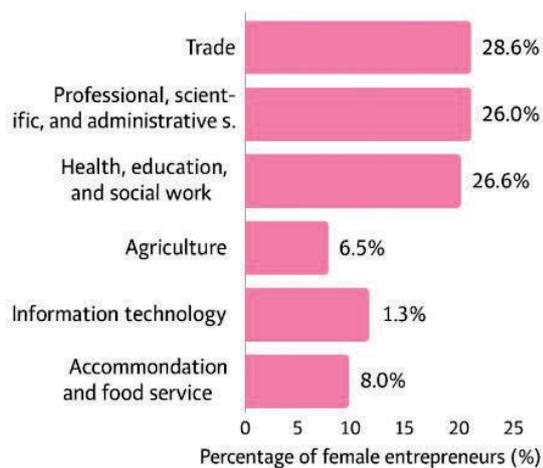


Fig.

Fig. 1.: Sectoral Distribution of Female Entrepreneurs in Hungary

(Source: compiled by the author based on [3])

B. The Dynamics of Female Entrepreneurial Motivation and Life-Cycle Characteristics

Identifying types of female entrepreneurs is essential for gaining a deeper understanding of their needs, motivations, and the challenges they face. Such insights make it possible to design more targeted support mechanisms, customized tools, and relevant resources that foster the sustainable growth of their businesses. Typology is also crucial because women start their ventures for diverse reasons, pursue different strategies to achieve their goals, and operate in varying economic and social contexts.

There are several theoretical approaches to classifying entrepreneurial motivations. Goffee and Scase categorized female entrepreneurs based on their relationship to traditional gender roles and their entrepreneurial value systems [4]. Moore distinguished between traditional and modern entrepreneurial types [5], while Langan-Fox and Roth approached the topic from a psychological perspective, identifying three main types: achievement-oriented, pragmatic, and managerial [6]. Mitra classified entrepreneurs into four groups based on motivational factors: young achievers, constraint-driven entrepreneurs, family-oriented entrepreneurs, and income-driven entrepreneurs [7].

These typologies highlight the multifaceted nature of women's entrepreneurial motivations, reflecting individual life situations, social norms, and access to economic opportunities. The study of entrepreneurial motivation is a central theme in economic and social research, as it fundamentally shapes the creation, operation, and long-term development of businesses.

In the case of female entrepreneurs, motivations often differ from those of men, closely linked to their attitudes toward social roles, family responsibilities, and the challenge of achieving work–life balance [8].

Based on the literature, entrepreneurial motivations can be analyzed along two primary dimensions:

- **Internal motivations**, such as the desire for independence, creativity, self-fulfillment, and value-driven activity;

- **External motivations**, such as labor market constraints, inflexible working environments, or the need for income generation.

In addition, motivations can also be classified as:

- **Pull factors** (e.g., professional development, flexibility, gaining social status), and

- **Push factors** (e.g., unemployment, job dissatisfaction, discrimination). ([9], [3])

Research consistently shows that among female entrepreneurs, internal, value-based motivations — such as self-fulfillment, autonomy, and social contribution — are often more influential than purely financial goals. For many women, entrepreneurship is not merely an economic activity, but a means of achieving personal growth, creative self-expression, and balance between family and professional roles. This perspective is particularly important in establishing work–life balance, which is often a top priority for female entrepreneurs.

It is essential to emphasize that women's entrepreneurial motivations are not static, but change dynamically depending on individual life situations, social roles, and life-cycle stages. The literature identifies several age- and life-stage-related types:

- *Young, independent entrepreneurs* are primarily motivated by the desire for autonomy, financial independence, and professional development [10]. Members of this group are often active in innovative, technology-oriented, or creative industries.

- *“Mompreneurs”*, i.e. mothers with young children, are typically driven by the need for flexibility and work–family balance. They often choose business models closely connected to motherhood, child-rearing, or family life, allowing them to work from home ([11], [12]).

- *Older women entrepreneurs* frequently start their ventures as a “second career”, utilizing their previous professional experience. Their motivations are dominated by the desire to remain active, contribute to society, and achieve self-fulfillment [13]. They are often engaged in consulting, mentoring, or nonprofit activities.

This life-cycle-based approach highlights that women's entrepreneurial motivations are not only diverse but also evolve over time, closely tied to the trajectory of their personal and professional lives. Understanding these motivations is therefore essential for designing targeted entrepreneurship development programs, support systems, and policy interventions.

C. Motivational Tools for Supporting Female Entrepreneurs

Maintaining entrepreneurial motivation throughout the entire business life cycle is of critical importance especially for female entrepreneurs, who often operate in complex roles across family, social, and professional dimensions. The following motivational tools offer practical support for women in entrepreneurship, helping sustain resilience and long-term commitment.

1. Personal Vision and Value-Based Mission

A personal vision and set of core values, such as helping others, creating social value, or achieving self-fulfillment, serve as powerful internal motivators. Clearly articulated goals and a mission statement help maintain focus, particularly in the early stages of entrepreneurship, when financial and emotional uncertainties are more pronounced [14]. Businesses that align with personal values are more sustainable and motivating in the long run.

2. Goal Setting and Strategic Planning

Regular goal setting and strategic planning are essential for sustaining motivation. Specific, measurable, and time-bound objectives, for example, using the SMART goal-setting method, enable entrepreneurs to track progress and navigate challenges effectively. Structuring goals in this way enhances the sense of self-efficacy, which directly supports sustained motivation.

3. Women's Entrepreneurial Communities and Networks

Belonging to women's entrepreneurial communities and being exposed to female role models and inspiring stories have a significant motivational impact. Supportive environments build confidence, reduce feelings of isolation, and create opportunities for experience-sharing, problem-solving, and business development. Through both online and offline networking, women entrepreneurs gain not only professional support but also emotional reinforcement an essential factor in overcoming entrepreneurial challenges [15].

4. Continuous Self-Development and Learning

Commitment to personal and professional growth is another strong motivational driver. Continuous learning, through courses, workshops, online programs, or professional literature, allows female entrepreneurs to stay up to date with market trends, enhance their competencies, and identify new opportunities. Self-development increases not only business success but also personal satisfaction and confidence.

5. Mentorship and Business Coaching

Mentorship is a structured learning process in which experienced entrepreneurs provide guidance, feedback, and direction to less experienced ones. For mentees, this process offers not only professional growth but also emotional support, particularly in times of stagnation or uncertainty. Mentors can serve as role models and help strengthen entrepreneurial identity. For women, mentorship and supportive networks are of outstanding importance, as they sustain long-term motivation and foster the development of entrepreneurial competencies [16].

III. EMPIRICAL RESEARCH

The aim of this research was to explore the motivational factors influencing women's decisions to start their own businesses. The study employed a quantitative methodological approach, using an online questionnaire for data collection. A total of 76 female entrepreneurs participated, representing various life situations, economic sectors, and business types. The questionnaire contained both closed and semi-open questions focusing on entrepreneurial motivations, professional background, and the balance between work and private life.

A. Results

Based on industry distribution, the largest proportion of respondents were active in the handicraft sector (22.4%), followed by the beauty industry (14.5%), marketing and consulting (both 10.5%), and trade (9.2%). The remaining 31.9% were distributed across sectors such as healthcare, education, information technology, financial services, hospitality and tourism, agriculture, manufacturing, sports, real estate, interpreting, construction, and security services. This industrial diversity clearly reflects the broad economic engagement of female entrepreneurs.

In terms of age distribution, most respondents were between 26 and 45 years old, indicating that the main target group consists of women in the active, career-building phase of life. Specifically, 9.2% were aged 18–25, 38.2% were 26–35, 31.6% were 36–45, 11.8% were 46–55, and 9.2% were over 55.

When analyzing motivational factors, flexible working hours emerged as the most influential driver, cited by 76.3% of respondents as their primary motivation. This was followed by financial independence (63.2%) and professional self-fulfillment (59.2%). Additionally, social value creation and community contribution played a significant role, especially among mothers with young children, for whom entrepreneurship often serves as a means to reconcile family life with professional ambitions.

These findings confirm previous literature suggesting that women’s entrepreneurial motivations are complex, shaped not only by economic but also by social and personal factors.

B. Motivational Factors by Life Situation

The results show that women’s entrepreneurial motivations are closely linked to their individual life circumstances and life-cycle stages. The following patterns emerged among respondents:

- *Young entrepreneurs* were primarily motivated by the desire for independence and career development. For this group, entrepreneurship serves as a means of self-realization and financial autonomy.

- *Among mothers with young children*, the most significant motivational factors were flexible working hours and family-friendly work organization. According to their responses, entrepreneurship enables them to harmonize motherhood with professional aspirations — consistent with international research on the “momprenneur” phenomenon ([11], [12]).

- *Older entrepreneurs* were mainly motivated by the opportunity to utilize prior knowledge and experience and to pursue a “second career.” For them, entrepreneurship often represents a way to remain active in later life and contribute to society through meaningful work.

The survey also highlighted that motivational factors are not static, but evolve dynamically over the entrepreneurial life cycle. In the early stages, *flexible work and livelihood needs* are typically the dominant drivers, while in later phases, *professional fulfillment, self-realization, long-term stability, and social value creation* gain importance.

These findings are consistent with international research trends, which indicate that women’s motivational patterns differ from those of men ([8], [14]). While men often prioritize financial success and business growth, women tend to place greater emphasis on *flexibility, value-based operation, and a family-oriented mindset*.

According to the survey, *flexible working hours* are highly significant for both mothers and women without children. Of the 76 respondents, 54 had children and 22 did not. The results show that although flexibility is particularly important among mothers, non-parent female entrepreneurs exhibited similar patterns. This suggests that flexibility is not solely a response to family obligations but a general need among women entrepreneurs, serving as a key element of work–life balance.

Self-fulfillment also emerged as a powerful motivational factor. The vast majority of respondents, regardless of parental status, stated that their business provides an opportunity to pursue personal and professional development. This supports the view that the drive for self-realization is not merely an individual ambition but a shared

value-driven force shaping women’s approach to entrepreneurship.

The evolution of these motivations over time aligns with the findings of the GEM 2023 global report [1], which notes that women-led businesses are increasingly adopting models focused on long-term sustainability and social value creation.

In conclusion, the research confirms that female entrepreneurial motivations follow distinct patterns, and recognizing these is crucial for developing the entrepreneurial ecosystem and designing targeted support programs. Strengthening the role of *flexibility, community support, and mentorship* is particularly important to enhance the long-term success and resilience of women entrepreneurs.

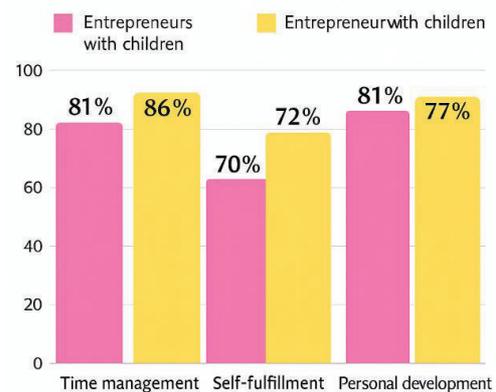


Fig. 2. Motivational Factors among Women with and without Children

(Source: compiled by the author based on research data)

Based on the responses, entrepreneurship represents far more than financial security for most women, it also plays a crucial role in personal growth and the strengthening of self-confidence. Both women with and without children predominantly agreed that their business significantly contributes to their independence and the development of their professional identity. This indicates that entrepreneurship serves as an identity-forming factor for women, fostering the unfolding of internal resources and long-term satisfaction.

The motivational patterns of mothers and non-mothers show many similarities. Flexibility in time management, the opportunity for self-fulfillment, and the desire for personal development appear as shared driving forces that stem not only from life circumstances but also from the fundamental motivations of women’s entrepreneurship.

IV. CONCLUSIONS AND RECOMMENDATIONS

The results of the research clearly indicate that female entrepreneurial motivations are highly diverse and are closely linked to individual life situations and the different stages of the entrepreneurial journey. The most frequently cited motivational factors include flexible time management, financial independence, and professional self-fulfillment, although their relative importance varies depending on age, family background, and previous experience.

Among young entrepreneurs, the dominant motivations are independence and career building, while for mothers with young children, flexibility and family-friendly business operation are of paramount importance. In contrast, among the older generation, motivations focus on utilizing previous knowledge and experience and the opportunity to pursue a second career.

From a practical perspective, the findings suggest that women's entrepreneurship should not be viewed merely as an economic activity, but as a value-based decision, one that places identity formation, personal development, and social engagement at its core. Therefore, entrepreneurship development programs should place greater emphasis on elements that promote flexible work arrangements, community and mentoring networks, and the strengthening of entrepreneurial self-confidence among women.

The role of mentorship and role models is particularly significant, as they provide not only professional guidance but also emotional support, fostering success at the start-up stage, perseverance, and long-term growth.

Overall, the research confirms that supporting female entrepreneurship holds both economic and social importance. By developing appropriate incentives and targeted support structures, female entrepreneurs can contribute even more effectively to sustainable, inclusive, and innovative economic development.

In recent decades, the economic and social participation of women entrepreneurs has become increasingly prominent. However, their motivations, decision-making mechanisms, and entrepreneurial patterns remain underrepresented in entrepreneurship research. Women's entrepreneurship should thus be understood not merely as an economic pursuit, but as a complex, value-driven decision, shaped by self-fulfillment, flexibility, social contribution, and personal life circumstances.

The present study aimed to identify the motivational factors influencing women's decisions to start a business, and to explore how these motivations evolve with age, family background, and entrepreneurial experience.

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The Role of Managerial Adaptation in Motivating and Communicating of Generations

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Abstract— This study examines the impact of intergenerational differences in the workplace on leadership, with a focus on motivation, communication, and leadership styles. It highlights how Baby Boomers, Generation X, Y, and Z differ in values, work attitudes, and motivational needs, posing complex challenges for leaders. The study emphasizes the importance of situational and adaptive leadership, coaching, emotional intelligence, and flexible approaches. Effectively managing generational diversity not only reduces conflicts but also fosters collaboration and enhances organizational performance. This study also serves as a preparation for a primary research project. The secondary literature review on how leaders manage, motivate, and communicate with different generations has supported the development of a questionnaire intended to be distributed among business owners, as well as senior and middle managers. In our next work, we will continue our research by processing and evaluating the primary data.

Keywords- Human Resources, Human Resources Management, Labor Market, Leadership, Motivation, Generations

I. INTRODUCTION

One of the main workplace challenges of our time is employee motivation and performance enhancement. The issue is further complicated by the growing generational diversity within workplaces today. Baby Boomers, currently between the ages of 61 and 79, are still present in the labour market. They find it difficult to step away from work, yet they possess extensive professional experience and expertise. Alongside them, Generation X employees, now aged between 44 and 60, have long contributed to the world of work. They are known for their diligence, though this often comes at the expense of a healthy work–life balance. Members of Generation Y, who are currently between 30 and 43 years old, tend to have lower lexical knowledge, but they place great importance on community and social relationships. The often-discussed Generation Z has also been part of the workforce for some time now; they are between 15 and 29 years old and are known as *digital natives*. Employers continue to explore the most effective ways to motivate this generation. Gradually, Generation Alpha is also entering the labour market, they are expected to challenge the power structures built by the Boomers and to shape an entirely new society.

Research suggests that the perception of a generational gap is a real phenomenon, and that perceived generational differences can often lead to workplace conflicts. Such conflicts frequently arise when people judge others based on their own assumptions and expectations. Given these factors, traditional leadership styles are no longer viable. When managing collaboration among different age

groups—each with its own motivations and perspectives—it is no longer possible to rely on a single leadership approach. When Kurt Lewin developed his theory of democratic, autocratic, and laissez-faire leadership styles in 1938, such generational differences did not yet exist. Today, this model can no longer be applied to the management of a modern workplace community, and even the later Blake–Mouton (1978) managerial grid model may not provide clear guidance for contemporary leadership.

To manage generational differences and especially their contrasting mindsets a differentiated leadership approach has become necessary. In situations where hierarchy-driven Boomers must work alongside Generation Z employees, who are fundamentally questioning and reshaping those hierarchies, standardized leadership practices and uniform motivational strategies simply cannot function effectively.

II. THE IMPACT OF GENERATIONAL DIFFERENCES ON LEADERSHIP

Let us examine the distinct values and attitudes toward work characteristic of different generations. Generational differences have a significant impact on leadership and workplace cooperation, as each age group possesses its own system of values, work attitudes, and motivational needs. These characteristics are summarized in Table 1.

The *Baby Boomer generation (1946–1964)* is typically loyal, persistent, and values stability, hierarchy, and traditional organizational structures. For them, security and recognition are the most important motivational factors, and in terms of leadership style, they tend to prefer traditional, authority-based approaches. Their life philosophy can be summarized by the saying: “*Hard work pays off.*”

Members of *Generation X (1965–1981)*, by contrast, are more independent and pragmatic. They take a responsible approach to work but also place great importance on maintaining a healthy work–life balance. They are primarily motivated by opportunities for development and the ability to work autonomously. Their motto might be: “*Work smart, not just hard.*”

The *Generation Y (1982–1995)*, consists of flexible, goal-oriented employees who actively seek challenges. They are motivated by meaningful work, continuous feedback, and opportunities for growth and personal freedom. Their guiding belief could be expressed as: “*My work should have purpose.*”

The youngest group, *Generation Z (1996–2010)*, were born into the digital age. They adapt quickly, value self-expression, and use technological tools naturally in their work. For them, flexibility, creativity, and authentic leadership are of particular importance. Their attitude is best summarized by the idea: *“I work, but my job doesn’t define who I am.”*

Table 1.: Generations' relationship to work and motivational characteristics (*own editing*)

Generation	Season	Attitude to work	Motivation	Key phrase
Baby boomer	1946–1964	Loyal, persistent, values stability and hierarchy.	Safety, recognition, traditional driving.	"Hard work pays off."
Generation X	1965–1981	In-dependent, responsible, practical.	Work-life balance, development.	"Work smart, not just a lot."
Generation Y	1982–1995	Flexible, goal-oriented, looking for challenges.	Meaningful work, feedback, freedom.	"My work should have meaning."
Generation Z	1996–2010	Digital, fast, self-expressive.	Flexibility, creativity, authentic leadership.	"I work, but work should not define who I am."

A. Maintaining the Integrity of the Specifications

As shown in Table 1, the key statements characterizing each generation differ significantly, which in itself carries the potential for collaboration challenges. These differences clearly illustrate how the diverse mindsets of generations can pose challenges for leaders. Managing cooperation among different age groups is a complex task, as leaders must be able to apply various motivational strategies to address distinct needs. While Baby Boomers are primarily motivated by recognition, members of Generation X value autonomy and professional responsibility. For Generation Y, providing meaningful goals and opportunities for personal and professional growth is the most effective way to inspire them, whereas members of Generation Z feel most engaged when they can express their creativity and enjoy technological freedom. All of this highlights that, in a multigenerational workplace, leaders must adopt a flexible and personalized approach to managing employee needs in order to build effective and harmonious teamwork. Due to these differing motivational perspectives, a leader working with multiple generations must tailor their motivational techniques accordingly. Boomers respond best to recognition, Generation X values independence, Generation Y seeks meaningful objectives and growth opportunities, while Generation Z is driven by creativity and digital freedom.

Table 2.: Communication and motivation of generations from the point of view of workplace leadership (*own editing*)

Generation	Communication style	What can motivate	Key leadership task
Baby boomer	formal, personal	recognition, appreciation	Evaluation of their experience

Generation	Communication style	What can motivate	Key leadership task
Generation X	Straightforward, logical	independence, flexibility	Trust and clear goals
Generation Y	Open, interactive	development, meaningful goal	Coaching and inspiration
Generation Z	digital, fast	credibility, creativity	Authentic, technology-friendly driving

As illustrated in Table 2, the communication styles, motivational factors, and leadership expectations of different generations fundamentally determine the success of leadership within an organization. Generational diversity has become increasingly characteristic of modern workplaces, posing complex challenges for leaders. Different age groups represent varying sets of values, expectations, and communication preferences. Generational differences are evident not only in values and motivation but also in communication styles and expectations toward leaders. Understanding these features on a systemic level has become one of the key challenges of modern leadership, as the labour market currently includes Baby Boomers, Generation X, Generation Y, and Generation Z each shaped by distinct social, technological, and cultural contexts. Therefore, the leader’s core task is not merely direction and control, but rather the harmonization of generational differences in communication and motivation, as well as the creation of an organizational culture in which every generation can find its place and value.

The *Baby Boomer generation* prefers formal, face-to-face communication, which is closely tied to traditional organizational hierarchies and requires the leader to demonstrate loyalty and recognition of experience. In contrast, *Generation X* values straightforward, logical communication and rational reasoning, with trust and clear goals at the center. For Boomers, leadership authority symbolizes organizational stability, while Generation X finds motivation in partnership rather than subordination. Consequently, for leaders this means that paternalistic management patterns must increasingly give way to trust-based, goal-oriented cooperation.

Generation Y, which seeks purpose and growth in their work, demands a more open and interactive style of communication. For them, the key role of a leader is to act as a coach and source of inspiration rather than as a controller. Effective collaboration with Generation Y therefore requires psychological safety and the joint definition of meaningful goals.

The emergence of *Generation Z* further expands the dimensions of leadership. Having grown up in the digital era, they respond best to fast, visual, and authentic communication. The leader’s key task in this case is to develop an authentic, technology-friendly leadership style that not only accepts but also integrates the digital competencies of younger employees into the organization’s functioning. For this generation, leadership success depends on authenticity and partnership, as they value personal integrity and inspirational example over formal authority.

Overall, the characteristics presented in the table clearly demonstrate that leadership priorities evolve from generation to generation: while earlier cohorts valued hierarchy, recognition, and respect for experience, newer generations place emphasis on trust, personal development, creativity, and authentic communication. For leaders, this means that the key to success lies in adaptive leadership—developing a flexible leadership style capable of

balancing stability with innovation, and experience with digital openness.

In multigenerational workplaces, leadership is no longer about control but about coordination, inspiration, and value creation, this is the defining task of 21st-century leaders. The most important responsibility of a leader in such an environment is to develop a flexible, personalized leadership approach. A successful leader recognizes that different generations communicate in different ways and are motivated by different factors and adjusts their leadership strategy accordingly. Leadership, therefore, is not merely a function of direction but an act of alignment and integration aimed at strengthening intergenerational cooperation, fostering mutual understanding, and enhancing organizational effectiveness. Baby Boomers prefer personal, face-to-face communication, and expect their leaders to provide tasks or praise through direct personal interaction. Generation X values logical reasoning and clear objectives, whereas Generation Y prefers interactive communication and responds best to coaching-based leadership. Generation Z, being technology-oriented, is comfortable with digital and even chat-based exchanges. These diverse expectations make it clear that leadership approaches cannot be uniform.

This is further confirmed by our earlier research [1], which found that leaders value different aspects of workplace behaviour, although certain shared elements appear in relation to motivation and skills. Similar conclusions were drawn by Szabó-Szentgróti [2], who found that “*intergenerational conflict can often be traced back to the misapplication of leadership and HR functions.*”

In the following section, we will examine the specific leadership application challenges that arise from these generational differences and explore possible solutions for addressing them.

III. TYPICAL LEADERSHIP CHALLENGES AND POSSIBLE SOLUTIONS: MANAGING STEREOTYPES AND GENERATIONAL SENSITIVITIES

A. Stereotypes

Just as in everyday life, workplace cooperation and leadership are also shaped by patterns and stereotypes. A **stereotype** is a simplified and generalized belief or assumption applied to members of a particular group (for example, based on gender, age, ethnicity, nationality, education, etc.) [3]. A related concept is the phenomenon of stereotype threat, which occurs when individuals fear confirming a negative stereotype about their group—leading to stress and decreased performance [4]. One common stereotype in the context of generational differences is the belief that Generation Z is lazy or uninterested in the world of work. However, this is not the only example. According to Szabó’s research [5], “*members of Generation X tend to cling to familiar forms, solutions, and values, and they find it difficult to change their way of thinking. The most strongly perceived stereotype was that they considered their own generation to be superior to the current one.*” It can therefore be assumed that deeply rooted stereotypes influence cooperation among generations. From a leadership perspective, this means that adapting to generational diversity is essential. Effective collaboration requires that task allocation not be based on generational affiliation, but rather on individual capabilities and preferences. Leaders should strive to identify common ground, foster points of connection, and establish a shared language among team members.

In social psychology, the theory of relative deprivation [6] highlights that dissatisfaction does not necessarily stem from a lack of material goods. During intergroup comparison, members of

relatively advantaged groups can also experience frustration. The need for recognition often outweighs the desire for material rewards.

Generational differences are particularly relevant in the context of workplace motivation and satisfaction, as each generation demonstrates distinct values, communication styles, and expectations for recognition. The concept of relative deprivation shows that dissatisfaction arises not merely from material inequality, but from how individuals perceive their position relative to others. This mechanism is especially relevant in intergenerational leadership, as different generations vary in their sensitivity to social comparison and recognition. For instance, Baby Boomers value acknowledgment of their experience and stability; if they perceive that younger colleagues receive preferential treatment, they may experience relative deprivation. For Generation X, providing autonomy and clear objectives reduces frustration and builds trust in leadership. Generation Y employees are motivated by development opportunities and meaningful goals; therefore, leaders should apply a coaching-oriented and feedback-rich approach. For Generation Z, authenticity, creativity, and technological freedom are vital—the leader must serve as an authentic role model with strong digital competence. Leadership, therefore, is not merely hierarchical direction but an adaptive, individualized intervention that takes into account generational sensitivities to social comparison. The conscious management of generational sensitivity is thus a fundamental prerequisite for effective, motivating, and sustainable leadership in today’s workplaces.

B. Segregation

A key objective in managing generational diversity is to avoid the formation of isolated generational clusters within the organization. Generations should not operate as separate entities, as this would only reinforce divisions and intensify intergroup tensions. Instead, collaboration should be built on shared goals, a common language, and mixed team composition. When boundaries within a team become more pronounced such as when a “young versus old” dichotomy emerges and this is reflected in communication or decision-making, it inevitably undermines trust and cooperation. To prevent such dynamics, leaders should aim to strengthen group cohesion, while maintaining flexibility and fairness in their approach. Generational differences can become a *source of strength* when the leader consciously integrates team members, applies transparent systems (in terms of goals, roles, and feedback), and manages motivational differences in a goal-aligned yet personalized way.

- “The leader consciously pairs team members.” This principle emphasizes the deliberate formation of *intergenerationally mixed teams*, allowing diverse skills, experiences, and perspectives to complement one another. For example, in a project team, the expertise of *senior employees can be combined with* the digital proficiency and innovation of *younger colleagues*.
- “The leader uses transparent systems (goals, roles, feedback).” Effective intergenerational collaboration requires clarity. The leader *must define objectives, roles, and feedback mechanisms clearly* so that each generation understands what is expected of them, minimizing the risk of misunderstanding or rivalry.
- “The leader addresses motivational differences through goal-aligned but personalized methods.” Each generation responds to different motivational factors. Baby Boomers value stability, Generation Y seeks meaningful work, and Generation Z desires creative freedom. The leader must employ *individualized motivational tools* that align all members toward a shared goal, while respecting personal preferences. This may involve *differentiated feedback styles, flexible working arrangements, or personalized task assignments*.

IV. The Concept of Differentiated Leadership

The differentiated (situational) leadership approach is grounded in the principle that leadership style should not be fixed but adapted to the follower’s level of competence and commitment.

- Situational leadership means that the leader adjusts their approach according to the employee’s developmental level and needs.
- Each employee has a unique motivational profile, reacting differently to factors such as recognition, growth opportunities, security, or innovation.
- Thus, it is not the leader’s style that remains constant, but rather the follower’s competence and engagement that determine how they should be led.

According to Rodic [7], drawing on Hersey and Blanchard’s situational leadership theory, most effective leaders prefer to adapt their leadership style to fit the specific context.

The Hersey–Blanchard model, a classical framework, identifies two key variables (Table 3.):

- Competence: the knowledge and practical experience relevant to the task
- Commitment: the motivation and confidence to perform the task

Combinations of these two dimensions yield four typical developmental (maturity) levels, each requiring a distinct leadership style.

Table 3.: Hersey–Blanchard model [7]

Subordinate position level	Characteristics	Matching style	What does a leader do?
D1 – low competence, high enthusiasm	New to the task	S1 Controller	Specific instructions, close follow-up
D2 – increasing competence, decreasing confidence	"I know how hard it is"	S2 Coach/Coaching	He explains, teaches, gives a lot of feedback
D3 – good competence, fluctuating commitment	He is capable of it, but he is uncertain	S3 Supporter	Encourages, involves you in the decision, shares responsibility
D4 – high competence and commitment	Independent expert	S4 Delegator	Agrees on goals, gives space, less frequent control

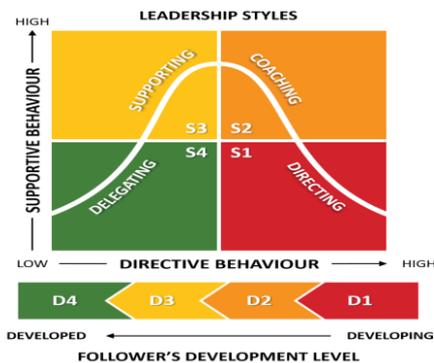


Fig.1.: Hersey – Blanchard Situational leadership styles [7]

The situational leadership model developed by Hersey and Blanchard assumes that there is no single ideal leadership style, as employees differ in their levels of competence and maturity. The effectiveness of a leader depends on their ability to adjust their behaviour according to the follower’s competence and motivation.

The model distinguishes four developmental levels (Fig.1.):

- **D1:** Individuals at this level possess *low competence but high enthusiasm*. They require *directive leadership (S1)*, where the leader provides clear instructions, close supervision, and explicit guidance.
- **D2:** At this stage, subordinates show *growing competence but declining confidence*. The most effective approach is *coaching-style leadership (S2)*, combining direction with emotional support and feedback to foster development.
- **D3:** This level is characterized by *adequate competence but fluctuating commitment*. Here, a *supportive leadership style (S3)* is appropriate, involving the employee in decision-making and strengthening their confidence through encouragement and participation.
- **D4:** At the highest maturity level, employees demonstrate *high competence and strong commitment*. The leader should adopt a *delegating style (S4)*, agreeing on objectives but allowing significant autonomy in how the work is carried out.

Generational differences, particularly in attitudes toward work, motivational patterns, and communication preferences, can be effectively mapped onto this situational leadership framework.

Younger generations, such as Generation Z and Generation Y, often exhibit the characteristics of D1–D2 levels, especially at the beginning of their careers, when they seek feedback, learning opportunities, and meaningful goals. For them, a coaching or developmental leadership style (S2) is the most effective, as it combines structure with mentoring and growth-oriented feedback.

In contrast, members of Generation X and the Baby Boomer generation typically display D3–D4 maturity, reflecting experience, accountability, and autonomy. They are best motivated through supportive or delegating leadership (S3–S4), which acknowledges their competence and provides independence while maintaining trust and open communication.

Thus, leadership flexibility across generations is a critical factor in organizational success. Effective leaders in a multigenerational environment recognize that age, experience, and motivational background not only create different needs but also require distinct leadership approaches. The situational leadership model therefore provides a conceptual framework for managing generational diversity constructively, enabling personalized support, targeted motivation, and the intentional development of individual career paths.

- Situational Leadership and the Practical Management of Generational Differences

A practical example of this approach is demonstrated by Magyar Telekom’s leadership development program, which applies a personalized system of development and motivation tailored to different generations. The company recognized that younger employees respond most positively to professional growth opportunities, technological challenges, and flexible working arrangements, while older colleagues are primarily motivated by recognition, opportunities to share their expertise, and involvement in decision-making processes. Accordingly, Telekom’s leaders employ a differentiated leadership toolkit: they conduct coaching and mentoring processes with younger employees, while involving more experienced generations in strategic decision-making. The Telekom example clearly illustrates that situational leadership is not merely a theoretical model but a practical guide for managing generational diversity. Such a leadership mindset fosters intergenerational trust

and learning, reduces conflicts arising from group boundaries, and strengthens organizational cohesion. Generational differences, therefore, should not be perceived as obstacles but as strategic resources, provided that leaders are able to adapt their leadership style to the maturity and motivational levels of their subordinates.

Ultimately, the leader's key task is to recognize what gives meaning to work for everyone. This awareness helps to mitigate stereotypes and reduce the phenomenon of separation among generational groups. In social psychology, this aligns with the contact hypothesis [8], originally formulated by Gordon Allport, which posits that prejudices and tensions between groups can be reduced when members of different groups engage in regular, direct, and positive contact under certain conditions. Even partial or indirect contact can lessen stereotypes if the interaction is associated with positive emotional experiences.

In the workplace, the contact hypothesis implies that structured collaboration among generations, based on shared goals and equality, can significantly reduce biases (for example, against younger or older employees). Therefore, the leader's role is to create an environment where different generations work together toward common objectives, learn from one another, and build trust, empathy, and cooperation through continuous interaction.

- Communication and Motivational Differentiation in Practice

In a previous study [1], we recorded the opinions of leaders from the Baby Boomer, Generation X, and Generation Y cohorts regarding leadership role models, leadership skills, and leadership motivation.

In the field of communication, notable generational differences can be observed. For Baby Boomers, a personal, respectful, and formal tone is preferred. Generation X values a pragmatic, direct, and results-oriented style, while Generation Y expects continuous feedback and two-way communication. The Z generation, in contrast, relies primarily on digital, concise, and visual messages, and appreciates quick responses. These distinctions indicate that even at the most fundamental level of interaction communication itself collaboration can be challenging due to differing expectations and communication norms.

Examining the deeper emotional dimensions of motivation, the Baby Boomers are primarily driven by stability, loyalty, and prestige. For Generation X, key motivators include autonomy, flexibility, and efficiency. Generation Y finds motivation in personal growth, meaningful work, and a sense of community, whereas the Z generation is inspired by innovation, technology, and social impact. These generational patterns highlight the importance of communication and motivational differentiation in leadership practice. Effective leaders recognize that each generation interprets respect, engagement, and success differently, and therefore tailor their communication style and motivational strategies to align with these diverse expectations.

V. THE IMPORTANCE OF KEY LEADERSHIP COMPETENCIES

It is evident that significant diversity exists in both communication and motivation across generations. To ensure effective collaboration among different generational groups, we argue that several key leadership competencies are indispensable.

- **Emotional Intelligence and Empathy**

The importance of emotional intelligence in leadership has been documented in previous research [9]. Motivational theories further support the notion that components of emotional intelligence are closely linked to employee motivation. Effective leaders leverage their internal resources and take into account the emotional states of their employees, thereby facilitating higher performance and engagement.

- **Flexible Leadership Style – Conscious Adaptation to Situations**

The combination of various leadership styles, along with the application of situational leadership, enables leaders to adapt effectively to generational differences. By consciously adjusting their approach to the competence, motivation, and needs of individual team members, leaders can foster a more inclusive, productive, and harmonious work environment.

Developing active listening and a "feedback culture"

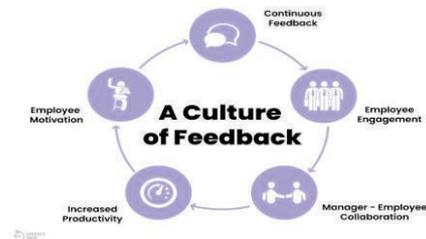


Fig.2.: Culture of Feedback [10]

A feedback culture encompasses dialogue, openness, continuous feedback, employee engagement, collaboration between employees and employers, striving for performance improvement, and employee motivation. Establishing such a culture is essential for sustaining productive and cohesive teams, particularly in multigenerational contexts (Fig.2.).

VI. Managing Multigenerational Teams

The knowledge of diverse social and relational systems, and the ability to integrate this understanding with management skills, is extremely important. The capacity to lead multigenerational teams is not innate but must be developed and learned. Leaders need to acquire a thorough understanding of generational differences and relate this knowledge to their leadership competencies.

The key to leadership effectiveness is adaptability: leaders must be able to adjust their style to the needs and experience of their followers. This approach aligns with Heifetz's theory of adaptive leadership [11], which views leadership as a dynamic, context-dependent process. Simultaneously, leaders must consciously avoid bias and discrimination in any form.

To manage intergenerational tensions, targeted strategies are recommended. For instance, if a conflict arises between employees from different age groups, it can be beneficial to involve intergenerational mediators (so-called *cuspers* or *tweeners*), who can bridge differing perspectives. An effective leader is committed to continuous learning, personal development, and the flexible adjustment of practices to enhance organizational performance [12].

The importance of leadership attitude is also supported by Kajtár [15], who highlights motivational leadership and a stimulating workplace environment as key factors influencing employees' workplace preferences and overall engagement.

A. Practical Experience

From personal experience at a large service corporation, where Generation Z employees make up approximately 10% of the total workforce, the company employs multiple strategies to engage newly entering employees. Orientation days, organized excursions, and active integration into the corporate culture are all designed to facilitate effective collaboration.

The company reflects the typical challenges of an aging workforce, with Baby Boomers and Generation X being the most prevalent. These groups were socialized within a hierarchical organizational culture, which at times can be difficult to reconcile with the flexibility and autonomy preferences of Generations Y and Z. With the arrival of younger generations, traditional corporate hierarchies have begun to loosen, creating opportunities for intergenerational mentorship. Boomers and Generation X members frequently act as mentors, guiding Y and Z employees through their

career paths. Special recognition is provided for mentorship work, thereby incentivizing collaboration. Such joint efforts often lead to strong interpersonal bonds across generations.

It is also characteristic that younger employees do not strictly follow the established paths of older generations; they introduce technological innovations, which gradually modify traditional practices within the company. One of the company's major objectives is to enhance collaboration across generations, with a key driving factor being the identification of shared goals. According to interviews conducted with employees from different generations, work outcomes serve as a common point of alignment, which acts as a bridge between generations [13].

The leadership example of Indra Nooyi, former CEO of PepsiCo, illustrates successful approaches to leading multigenerational teams. Under Nooyi's leadership, diversity and inclusivity were prioritized, ensuring that employees from different backgrounds and experiences felt valued. To promote intergenerational collaboration, younger and more experienced employees worked together in cross-functional teams, allowing fresh ideas to merge with established knowledge. Nooyi's leadership style emphasized openness and accessibility: she communicated personally, listened to feedback, and fostered an inclusive environment focusing not only on hierarchy but also on collaboration.

These efforts combined business success with human performance. They were not merely "good practices"; they contributed to employee satisfaction, engagement, and ultimately tangible business results.

VII. CONCLUSION

Workplace conflicts between generations often arise because individuals rely on stereotypes, tending to notice and remember information that confirms preexisting beliefs. Raising awareness of generational stereotypes can influence behaviour and interactions with employees. However, leaders should focus not on stereotypes, but on the perspectives, needs, and talents of individuals.

The sources of intergenerational workplace conflict frequently lie in differing assumptions, values, and expectations. Older employees typically value seniority and professional experience, while younger generations tend to prioritize technological proficiency and innovation. Consequently, both explicit and implicit generational biases can affect workplace communication and collaboration.

For leaders, it is therefore essential to strive for a deeper understanding of generational perspectives and experiences, clearly communicate expectations, encourage accountability, and ensure opportunities for individual development and regular, constructive feedback. Such practices contribute to the establishment of a trust-based and inclusive organizational culture.

Differentiated leadership does not divide generations but connects them. This connection enhances performance and fosters an understanding of differences. The contact hypothesis suggests that structured, meaningful interaction reduces stereotypes and increases cooperation. Effective leaders recognize that while the goal may be shared, the path to achieving it must be personalized. They consider generational differences and apply management approaches accordingly.

Currently, only a small proportion of organizations approximately 10% integrate a multigenerational approach into leadership development programs, even though most leaders (over 75%) recognize generational differences as relevant for leadership style. Leadership development is therefore most effective when coaching competencies are enhanced alongside generational awareness. These competencies include self-awareness, cultural openness, reflective observation, interpersonal relationship building, and adaptive leadership behaviour [14]. It is important to note, however, that generational training alone does not necessarily reduce biases and may, in some cases, reinforce them. Thus, creating a

workplace environment that promotes open communication, mutual understanding, and collaboration is essential.

Generational differences are not problems but resources when consciously managed. These differences can be transformed into added value if leaders intentionally organize work to leverage them. To activate these resources, several key competencies are indispensable, including emotional intelligence (EQ), a culture of feedback, and a flexible leadership style. Achieving performance growth requires a combination of tools to bridge the diverse perspectives and values of different generations. A central leadership task is the ability to adapt to situational needs, mitigating stereotypes and assumptions while enhancing the effectiveness of collaboration.

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On Estimating the Risk of an Investment Portfolio

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Abstract — According to Markowitz's classic approach, the risk of an investment portfolio is determined by the standard deviation of its return. Two other risk assessment methods are considered in this paper. One calculates the so-called VaR (Value at Risk), while the other calculates the standard deviation for a portfolio return not exceeding the mean return. A computational formula is derived for the latter. In the typical case of continuous return distribution, some simpler and more convenient definition for VaR is given. These three risk assessment methods are compared between each other.

Keywords — Markowitz approach, investment portfolio, return, risk, standard deviation, semi-deviation, VaR.

An investment portfolio is a set of securities acquired by an investor in the present to get income in the future. Such a portfolio is defined by a set of numbers $(p_1; \dots; p_i; \dots; p_N)$ representing the shares of capital invested in each of securities, where N is the number of securities in the investment portfolio. Herewith

$$p_1 + \dots + p_i + \dots + p_N = 1 \quad p_i \geq 0$$

The return of the i^{th} security is expressed by the following formula:

$$r_{it} = \frac{q_{it} - q_{i(t-1)}}{q_{i(t-1)}}$$

where q_{it} and $q_{i(t-1)}$ are the security quotes at times t and $t - 1$.

The return r_{pt} of the investment portfolio at time t is expressed as follows:

$$r_{pt} = \sum_{i=1}^N p_i r_{it}$$

Assuming that T is the current moment in time, it is necessary to predict the portfolio return at the next time $T + 1$. Denote this random variable as $R_{p(T+1)}$. The predicted value of $R_{p(T+1)}$ is the mathematical expectation:

$$E[R_{p(T+1)}] = E \left[\sum_{i=1}^N p_i R_{i(T+1)} \right] = \sum_{i=1}^N p_i \cdot E[R_{i(T+1)}]$$

where $R_{i(T+1)}$ is a random variable representing the i^{th} security return at time $T + 1$.

Using historical data, it is possible to calculate a statistical estimate for the value $E[R_{i(T+1)}]$ as the mean \bar{r}_i of the i^{th} security returns over the entire previous period:

$$E[R_{i(T+1)}] \approx \bar{r}_i = \frac{1}{T-1} \sum_{t=2}^T r_{it}$$

H. Markowitz proposed using the standard deviation σ of the investment portfolio return as a measure of the risk [1]. Herewith the variance σ_i^2 of the i^{th} security return at time $T + 1$ is given by the formula:

$$\sigma_i^2 = E \left[(R_{i(T+1)} - E[R_{i(T+1)}])^2 \right]$$

Sample estimate of the variance of the i^{th} security looks like:

$$\sigma_i^2 \approx s_i^2 = \frac{1}{T-2} \sum_{t=2}^T (r_{it} - \bar{r}_i)^2$$

When using all the above formulas, the time series r_{it} of each security returns was implicitly assumed to be ergodic and, accordingly, stationary [2]. It is difficult to verify the ergodicity in practice, so they usually limit themselves to checking only stationarity. A new method for checking the stationarity of time series is presented in [3].

It is important for an investor to have a forecast of a possible loss. If the standard deviation σ is used as a measure of the risk, and the distribution of the investment portfolio returns is asymmetric, not quite correct estimate for the return decrease (or the loss) may be obtained.

In the case of asymmetry in the return distribution, a more adequate measure of the risk is the standard deviation σ of such the portfolio returns that do not exceed their mean return [4]. Let's call this indicator the Standard Down Deviation (SDD). If $\sigma_- > \sigma$, then using σ as a risk measure would result in the underestimation of return decrease from its expected (i.e. mean) value. If $\sigma_- < \sigma$, then using σ as a risk measure would result in the unjustified overestimation of return decrease.

Let's calculate the SDD of the i^{th} security returns. Suppose that among the returns r_{it} at $t > 1$ there are \tilde{T} values $r_{it_1}, r_{it_2}, \dots, r_{it_{\tilde{T}}}$ satisfying the condition $r_{it} < \bar{r}_i$. The following statistical estimate is used for calculating SDD σ_- :

$$\sigma_- \approx \tilde{s}_i, \quad \tilde{s}_i^2 = \frac{1}{\tilde{T}-1} \sum_{j=1}^{\tilde{T}} (r_{it_j} - \bar{r}_i)^2$$

The variance of portfolio returns at the future time $T + 1$ is given by the formula:

$$\sigma^2[R_{p(T+1)}] = \sum_{i=1}^N \sum_{j=1}^N p_i p_j \text{cov}_{ij}$$

where cov_{ij} is the covariance of the i^{th} and j^{th} security returns (remark $\text{cov}_{ii} = \sigma_i^2$).

Using historical data on securities returns, the covariance can be estimated by means of the following approximate formula:

$$\text{cov}_{ij} \approx \frac{1}{T-2} \sum_{t=2}^T (r_{it} - \bar{r}_i) \cdot (r_{jt} - \bar{r}_j)$$

In this paper one proposes a method for calculating SDD σ_- for a securities portfolio. It consists of the following.

Let's denote by R_{pt} the investment portfolio return and by R_{it} the i^{th} security return at time $t = 1, 2, \dots, T, \dots$ for each $i = 1, 2, \dots, N$. These random functions (random processes) are assumed to be ergodic. It was shown in [3] that the ergodicity condition is necessary for application of the effective portfolio theory [1] to be mathematically correct [5]. We have the following equations:

$$R_{pt} = \sum_{i=1}^N p_i R_{it} \quad E[R_{pt}] = \sum_{i=1}^N p_i E[R_{it}]$$

Due to the supposed ergodicity of the time series of securities returns (i.e., the ergodicity of random functions R_{it} [2]), the mean returns $E[R_{it}]$ and $E[R_{pt}]$ as well as the standard deviations $\sigma_i = \sigma[R_{it}]$ and $\sigma = \sigma[R_{pt}]$ do not depend on t .

Now we are ready to describe a statistical estimate s_- for the SDD σ_- of portfolio returns. If among the actual returns r_{pt} at $t > 1$ there are \bar{T} values $r_{pt_1}, r_{pt_2}, \dots, r_{pt_{\bar{T}}}$ satisfying the condition $r_{pt} < \bar{r}_p$, the following statistical estimate is used for calculating σ_- :

$$\sigma_- \approx s_- , \quad s_-^2 = \frac{1}{\bar{T}-1} \sum_{j=1}^{\bar{T}} (r_{pt_j} - \bar{r}_p)^2 , \quad \bar{r}_p = \sum_{i=1}^N p_i \bar{r}_i$$

The above considered risk measures for an investment portfolio allow us to estimate the deviation of its return from the mean. Another measure of risk that directly indicates the loss is VaR (Value at Risk). It is interpreted as the maximum possible loss value for a given confidence probability. In other words, for a given significance level α the probable loss does not exceed VaR with the probability $1 - \alpha$. However, in general case this definition is mathematically ambiguous. Consider examples 12.3, 12.4 on page 258 [6]. "A one-year project has a 98% chance of leading to a gain of \$2 million, a 1.5% chance of leading to a loss of \$4 million and a 0.5% chance of leading to a loss of \$10 million. There is a probability of 0.5% of any specified loss level between \$4 and \$10 million being exceeded. VaR is therefore not uniquely defined. One reasonable convention in this type of situation is to set VaR equal to the midpoint of the range of possible VaR values. This means that, in this case, VaR would equal \$7 million".

However, it is difficult agree this opinion of the author [6], since from the practical point of view it would be much more informative to state that VaR is equal to 4 million dollars. Accordingly, well-known formula (1) should be used:

$$VaR_{1-\alpha} = \inf\{x: P(-r_p > x) \leq \alpha\} \quad (1)$$

where r_p is the portfolio return ($-r_p$ is correspondingly the loss), and α is the significance level at which $VaR_{1-\alpha}$ is calculated.

However, when analyzing formula (1) a hypothesis has arisen that the risk measure $VaR_{1-\alpha}$ is nothing else than the quantile of the loss distribution for a given probability $1 - \alpha$. As it turned out, this hypothesis is true under some restrictions on the loss distribution function. This result is presented in the following statement

Proposition 1: *Suppose the losses of an investment portfolio have a continuous distribution, and different values of the loss (which could occur in reality) are corresponded by different values of the losses distribution function. Then, for any given significance level α the risk estimate $VaR_{1-\alpha}$ is the $(1 - \alpha)$ -quantile of the losses distribution.*

Proof:

It follows from the condition of Proposition 1 that all the possible loss values fill an interval (half-interval, segment). In all further considerations the variables $x, x', y, \pm r_p$ are assumed to take their values in this interval (half-interval, segment).

Let the inequality $P(-r_p > x) \leq \alpha$ holds for some x . We can rewrite this as $P(r_p < -x) \leq \alpha$. If $P(r_p < -x) = \alpha$, then $-x$ is the α -quantile of the portfolio returns distribution while x is the $(1 - \alpha)$ -quantile of the losses distribution.

Let's verify the following equality:

$$x = \inf\{x': P(-r_p > x') \leq \alpha\} = VaR_{1-\alpha} \quad (2)$$

Since $P(-r_p > x) = \alpha$, then when $P(-r_p > y) \leq \alpha$ there takes place $x \leq y$ (if $x > y$, then $P(-r_p > y) > P(-r_p > x) = \alpha$ which contradicts to $P(-r_p > y) \leq \alpha$).

The case $P(-r_p > y) = P(-r_p > x)$ is impossible here, otherwise the values of the distribution function at points x and y would be equal which contradicts to Proposition 1).

Thus, it has been proved that x is a lower bound for the set $\{x': P(-r_p > x') \leq \alpha\}$. Since $x \in \{x': P(-r_p > x') \leq \alpha\}$, then $x = \inf\{x': P(-r_p > x') \leq \alpha\}$.

Assume that $P(r_p < -x) < \alpha$, i.e., $P(-r_p > x) < \alpha$.

It is clear, the smaller x the higher the probability of the event $-r_p > x$. With a continuous decrease in x the value of $P(-r_p > x)$ increases continuously and, it would seem, the value should become equal to α at a certain value of x . However, the situation is theoretically possible when, for a certain number $0 < \beta < \alpha$, for all values of x obtained during the decreasing process we have $P(-r_p > x) \leq \beta$. That is, $P(r_p < -x) \leq \beta$ and the value of $P(r_p < -x)$ indefinitely approaches β as x decreases. In such a situation, for any

sufficiently small x we have $P(r_p < -x) \leq \beta$. This contradicts to the fact that

$$\lim_{-x \rightarrow +\infty} F_{r_p}(-x) = 1$$

where F_{r_p} is the portfolio returns distribution function.

Thus, for some x satisfying $P(-r_p > x) \leq \alpha$ there takes place $P(-r_p > x) = \alpha$. Since this x is the $(1 - \alpha)$ -quantile of the losses distribution, the Proposition 1 is proved.

The condition imposed on continuously distributed portfolio losses in Proposition 1 is not restrictive and, obviously, fulfilled in all economically realistic situations. Therefore, for the practical application of Proposition 1 it is sufficient the portfolio losses could be modelled by a random variable with continuous distribution. Proposition 1 is not applicable in the case of discrete losses distribution, formula (1) should be used instead.

Among the considered measures for the risk of loss (or decrease of return) resulted from investing in a securities

portfolio, SDD and VaR should be highlighted. If SDD allows the investor to estimate the possible decrease of expected return, then VaR gives a representation of how significant the loss may be. The combination of these two indicators will help in making more informed decision.

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SESSIONS V.

Education

Exploring Industry Perspectives on Dual Education

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Abstract— The aim of this study is to present the operational experiences of dual education at the Alba Regia Faculty of Obuda University, with particular emphasis on the perspectives of corporate partners. The empirical research analyzes responses from corporate partners using a questionnaire-based methodology. According to corporate feedback, dual education contributes in the long term to the supply of skilled labor, the shaping of organizational culture, and the development of operational competencies. However, the implementation of the system poses structural and resource-related challenges, especially in the areas of mentoring and student retention. The findings of the research highlight that the effectiveness of dual education can be further enhanced through closer university-industry collaboration, more flexible training structures, and targeted competency development.

Keywords—Dual Education, Industry-University Partnership, Work-Based Learning, Corporate Feedback

I. INTRODUCTION

Collaboration between higher education and industry has become increasingly prominent in recent years, particularly in the fields of engineering and information technology, where practical knowledge and labor market relevance play a crucial role. Dual education emerged in Hungary in 2015 as an educational model that enables the integration of theoretical knowledge with corporate practice. The Alba Regia Faculty of Obuda University was among the first institutions to implement this training format [1], [2], [3], which has since become one of the faculty's key educational pillars.

Students participating in dual education pursue their studies simultaneously at the university and with a corporate partner, thereby gaining real work experience during their academic training. This not only facilitates the development of professional competencies but also eases the transition into the labor market [4]. For corporate partners, dual education offers an opportunity to become familiar with students' work ethic, mindset, and professional development during the training period, thereby reducing recruitment risks and enhancing employee loyalty.

The aim of the present study is to explore, through empirical research, the experiences, evaluations, and development proposals of corporate partners involved in dual education. The questionnaire-based data collection enabled the structured gathering of companies' opinions regarding the benefits, challenges, and future cooperation opportunities related to the training model. The results of the research may contribute to the further development of the dual education model and to strengthening the relationship between the university and industry.

II. HIGHER EDUCATION AND ECONOMIC COLLABORATION

Collaboration between higher education institutions and industrial stakeholders has become a key factor in ensuring the quality and labor market relevance of academic programs. The rapidly changing demands of the economy, the pace of technological advancement, and labor market expectations present complex challenges that universities alone can hardly address quickly and effectively. Close cooperation with industry partners enables training content to remain up to date, provides students with practical knowledge, and ensures that graduates enter the workforce with truly marketable competencies [5], [6].

In the fields of engineering, information technology, and applied sciences, industrial collaboration is particularly crucial, as these sectors require the rapid integration of technological innovations, the use of modern tools, and an understanding of real-world industrial challenges to support students' professional development [2], [6]. Involving industry partners in curriculum development, project-based learning, and the organization of internships significantly enhances the practical orientation and credibility of academic programs [8].

One of the most structured forms of such collaboration is dual education, in which theoretical instruction and corporate practice are closely integrated [5]. This model provides students with the opportunity to gain experience in real work environments during their studies, while companies actively participate in training future professionals [6], [7]. This not only facilitates professional socialization but also contributes to understanding corporate culture, shaping employee attitudes, and, in the long term, strengthening workforce retention [8], [10].

Based on the preferences of Generation Z engineering students, flexibility, a technologically advanced environment, and work-life balance are key considerations in shaping future workplaces [1]. In this context, dual education serves not only as a platform for developing professional skills but also for enhancing social competencies, particularly when corporate partners are actively involved in the training process [2], [7].

According to corporate feedback, practical training becomes more effective when companies and universities jointly design the curriculum and training structure [6]. This tripartite collaboration between the student, the university, and the company enables the training system to respond flexibly to economic and technological changes, while students acquire professional competencies through engagement with real-world problems [5], [9].

Comparative academic performance data indicate that students enrolled in dual education programs tend to achieve better results and exhibit lower dropout rates [5], [9]. For companies, this translates into access to more motivated and goal-oriented young professionals who become familiar with corporate culture and expectations during their studies. The effectiveness of dual education is thus reflected not only in the quality of education but also in the successful integration of graduates into the labor market [10].

Research examining efficiency and satisfaction suggests that dual education can be a sustainable model in the long term, especially when companies go beyond providing internship placements and actively engage in mentoring and evaluating students [8]. This type of collaboration benefits not only students but also companies, as fresh knowledge and innovative perspectives can be directly integrated into corporate operations [6], [11].

III. SAMPLE CHARACTERISTICS AND SECTORAL REPRESENTATION

This section presents the sample of corporate partners participating in the survey, focusing on their evaluations of dual education experiences. The aim was to assess how companies perceive the time spent by dual students at their organizations, including the perceived advantages and disadvantages of the training model. The questionnaire addressed the range of skills and competencies considered important and fostered through dual education, as well as satisfaction with students' preparedness and university-acquired knowledge. Respondents were also invited to suggest improvements to enhance the effectiveness of the dual education system.

A total of $N=44$ responses were collected, all from professionals directly involved with dual students. The survey was conducted anonymously, and therefore no personal or company-specific identifiers were recorded. However, respondents provided information on company size, categorized as follows:

- Large enterprises (more than 250 employees): 75% ($N=33$)
- Medium-sized enterprises (50–249 employees): 18.2% ($N=8$)
- Small enterprises (10–49 employees): 6.8% ($N=3$)

The companies' fields of activity were classified into eight categories. The most represented sectors were:

- Transportation and logistics: 36.4% ($N=16$)
- IT services, operations, and development: 20.5% ($N=9$)
- Manufacturing and processing industries: 15.9% ($N=7$)

Moderate representation was observed in:

- Public administration and services: 11.4% ($N=5$)
- Other engineering activities: 6.8% ($N=3$)

Lower representation was found in:

- Utilities: 4.5% ($N=2$)

- Financial institutions and sports federations: each 2.3% ($N=1$)

IV. FINDINGS ON THE EFFECTIVENESS AND CHALLENGES OF DUAL EDUCATION

A. Strategic Advantages of Dual Education from the Corporate Perspective

The benefits of dual education from the viewpoint of corporate partners can be grouped into three main categories. A significant majority of respondents (75%, $N=33$) identified the long-term provision of skilled labor as the primary advantage, particularly among large enterprises (78%) and medium-sized companies (75%), across nearly all sectors.

The second most frequently cited benefit (64%, $N=28$) was the transfer of organizational culture and company-specific knowledge during the dual education period, serving as a medium-term competency development goal. Statistical analysis revealed a significant relationship between company size and the perceived importance of company-specific knowledge transfer, as confirmed by both the Pearson chi-square test ($\chi^2(2) = 6.351, p = 0.042$) and Spearman's rank correlation ($r_s = .300, p = 0.048$). Both large enterprises (72.7%) and small businesses (66.7%) emphasized the importance of transmitting company-specific knowledge to students as potential future employees, while medium-sized enterprises considered this aspect less critical (25.0%). The emphasis on company-specific knowledge is justified by the complex organizational structures and specialized processes of large enterprises, and by the need to maintain competitiveness in small businesses.

A moderately emphasized benefit (48%, $N=21$), primarily reported by respondents from large enterprises (55%, $N=18$), was the potential of practically trained, immediately deployable employees, reflecting short-term operational skill development. The presence of practically skilled personnel is particularly valuable in large organizational environments, where the operational resolution of everyday tasks and challenges is essential.

Overall, the corporate value proposition of dual education is multi-layered, ranging from long-term human resource strategies (75%), through medium-term organizational knowledge management goals (64%), to short-term operational skill development (48%). Dual education not only holds societal and economic significance but also offers a proactive response to labor market challenges. The responses clearly indicate strong corporate commitment to the dual education model and a recognition of its forward-looking benefits.

B. Structural and Operational Challenges in Implementing Dual Education

Despite the numerous benefits of dual education, its implementation and supervision on the corporate side present several structural and operational challenges. One of the most significant difficulties is integrating the mentoring and training of young, often inexperienced students into the daily routines of company employees. This responsibility places a considerable burden on mentors, particularly during the initial phase of the training period.

Survey responses reflect this reality: 75% of respondents ($N=33$) identified the time and resource demands of mentoring as the primary challenge. This issue was especially

emphasized by medium-sized enterprises, where the availability of qualified mentors and the time they can dedicate to student supervision may be limited.

The second most frequently mentioned challenge (41%, $N = 18$) was student attrition after graduation. Although correlation analysis revealed only marginal statistical significance between company size and student attrition ($r_p = .290$, $p = 0.056$; $r_s = .279$, $p = 0.067$; $\chi^2 = 3.698$, $p = 0.157$), a clear trend emerged: large enterprises reported higher rates of post-graduation attrition (49%, $N = 33$), while small enterprises retained all their dual students (0% attrition, $N = 3$). This paradox highlights a key tension: although large companies view dual education as a strategic tool for long-term talent acquisition (75%), nearly half report losing students after graduation.

This discrepancy may be explained by differences in organizational culture. Smaller firms often offer a more personal, family-like work environment that fosters stronger emotional bonds, while larger firms, despite offering more structured training, may struggle with retention due to less personal engagement and greater external competition for skilled graduates. Additionally, some large companies may not have open positions available at the end of the training period, even if they are satisfied with the students' performance. This structural limitation is often tied to longer planning cycles in large organizations.

To address this issue, an institutional recommendation has been proposed: allowing students to complete their final academic year under an individual study schedule. This flexible arrangement could enable students to transition more easily into full-time employment if a relevant position becomes available before graduation.

The least frequently cited challenge (11%, $N = 5$) was the insufficient theoretical knowledge of students. Overall, the theoretical preparation of dual students was rated positively, which is an encouraging reflection on the quality of university education. However, this issue was more concentrated in the manufacturing, IT, and transportation sectors, where specific technical knowledge is often critical.

C. Development Priorities of Key Competencies in the Dual Education Framework

One of the objectives of the survey was to identify which skills and competencies corporate stakeholders consider most important to develop within the dual education framework. Respondents were asked to evaluate eight key competencies grouped into four broader categories:

- Technical competencies: professional knowledge and practical skills
- Cognitive competencies: problem-solving and critical thinking
- Interpersonal competencies: communication and teamwork
- Personal development: responsibility and autonomy

The results show a clear dominance of technical competencies, which were prioritized by 51% of respondents, particularly among medium-sized enterprises (50%, $N = 4$) and within the public administration and services sector (80%, $N = 4$). Cognitive competencies were the second most emphasized category (36%), especially in large enterprises

and the transportation and logistics sector, where both problem-solving and critical thinking were simultaneously highlighted (18%, $N = 3$). Personal development (32%) was most relevant in large enterprises, particularly in the IT sector, while interpersonal competencies (31%) showed a relatively balanced distribution across company sizes and sectors. These findings reflect the practice-oriented nature of dual education, where technical expertise is considered the most critical outcome.

The most highly valued competencies were problem-solving (64%, $N = 28$) and professional knowledge (61%, $N = 27$), significantly ahead of other skill areas. Professional knowledge was especially emphasized in medium-sized enterprises (75%, $N = 6$) and in public administration (100%, $N = 5$), utilities (100%, $N = 2$), manufacturing (72%, $N = 5$), and financial sectors (100%, $N = 1$). Similarly, problem-solving was strongly prioritized by medium-sized enterprises (75%, $N = 6$), particularly in manufacturing (72%, $N = 5$) and transportation (81%, $N = 13$).

In the mid-priority range, autonomy (41%, $N = 18$), practical skills (41%, $N = 18$), communication (32%, $N = 14$), and teamwork (30%, $N = 13$) were identified. Autonomy was most emphasized by small enterprises (67%, $N = 2$), with the IT services and operations sector showing the highest demand (78%, $N = 7$). A statistically significant relationship was found between practical skills and company size ($\chi^2 = 6.205$, $p = 0.045$), with medium-sized enterprises showing the highest demand (75%, $N = 6$), compared to large enterprises (36%, $N = 12$) and small enterprises (0%, $N = 0$). The public administration sector also showed a strong preference for practical skills (80%, $N = 4$). Communication and teamwork were evenly distributed across company sizes and sectors. The lowest priority competencies were responsibility (23%, $N = 10$) and critical thinking (9%, $N = 4$).

D. Corporate Evaluation of Student Preparedness in Dual Education

Corporate partners expressed a high level of satisfaction with the preparedness of students participating in dual education programs ($N = 44$). On a 5-point Likert scale, the average satisfaction score was $\bar{\chi} = 4.30$ ($SD = 0.553$), indicating a position between the "satisfied" and "fully satisfied" categories.

Importantly, no negative responses were recorded; all ratings fell within the 3-5 range. These results underscore the perceived effectiveness of the dual education model from the corporate perspective. According to the respondents, students' preparedness aligns well with labor market expectations, and no major deficiencies were identified.

Neither company size nor sectoral affiliation showed statistically significant correlations with satisfaction levels. However, a more differentiated pattern was observed among large enterprises, while small and medium-sized companies tended to provide more homogeneous and consistently positive evaluations. Sectoral differences may reflect specific training needs, suggesting that certain industries place greater emphasis on aspects of student preparedness.

E. Recommendations for Enhancing the Effectiveness of the Dual Education System

In the survey, 66% of respondents ($N = 29$) shared suggestions for improving the effectiveness of the dual

education model. These responses were analyzed using content analysis and categorized into thematic groups. The most frequently mentioned category (28%, $N = 8$) focused on structural and scheduling improvements to the practical training component. Respondents proposed extending the duration of practical training during the academic term, currently limited to one day per week, and suggested implementing continuous practical blocks, if timetables allow. This would facilitate more meaningful student involvement in real work tasks and help overcome initial adaptation challenges more efficiently.

The second most common recommendation (24%, $N = 7$) emphasized the need for closer collaboration between universities and companies, including the development of communication channels and the institutionalization of regular faculty and mentor visits to both academic and corporate environments.

A significant portion of respondents (21%, $N = 6$) proposed curriculum development, calling for the introduction of more company-specific courses, increased emphasis on practice-oriented teaching, and a better balance between theoretical and practical content. While theoretical instruction still dominates in higher education, there is a growing demand for applied learning methods and content.

Another group of suggestions (17%, $N = 5$) highlighted the importance of developing soft skills and workplace attitudes, such as precision, motivation, and responsibility, competencies often associated with generational characteristics in the labor market. A smaller group (10%, $N = 3$) addressed administrative burdens and recommended improvements to information and support systems to streamline processes for both students and companies.

Overall, the findings confirm that dual education creates clear value for companies, particularly in terms of long-term workforce development, company-specific knowledge transfer, and operational skill-building. However, challenges such as resource-intensive mentoring and post-graduation student attrition point to the need for strategic responses.

The identified competency development priorities and collaboration proposals suggest that the future of dual education lies in more flexible training structures, stronger university-industry partnerships, and enhanced practice-oriented instruction. Personalization of programs and the refinement of incentive systems are expected to further strengthen cooperation among stakeholders in the coming years.

V. CONCLUSION AND STRATEGIC OUTLOOK

The findings of this study confirm that dual education represents a strategically valuable model for aligning higher education with the evolving needs of the labor market. From the perspective of corporate partners, the system offers clear advantages in terms of long-term workforce development, the transmission of company-specific knowledge, and the cultivation of operational competencies. These benefits are particularly pronounced in sectors where technological innovation and practical expertise are critical to competitiveness.

At the same time, the research has revealed several structural and operational challenges that must be addressed to ensure the sustainability and scalability of the model. The

mentoring of students, especially those with limited prior experience, places a significant burden on company staff, particularly in medium-sized enterprises where human resources are often stretched. Furthermore, the issue of student attrition after graduation, especially in large organizations, highlights the need for more effective retention strategies and better alignment between training outcomes and employment opportunities.

The analysis of competency development priorities underscores the dominant role of technical and problem-solving skills in dual education, while also pointing to the growing importance of soft skills such as autonomy, communication, and teamwork. These findings suggest that the dual education model must continue to evolve in response to generational shifts in student expectations and workplace dynamics.

To enhance the effectiveness of the system, several directions for development have emerged. These include the extension and restructuring of practical training periods to allow for deeper integration into company workflows, the strengthening of university-industry collaboration through more regular and structured communication, and the refinement of curricula to better balance theoretical knowledge with practical application. Additionally, the development of soft skills and workplace attitudes should be more explicitly embedded in training programs, while administrative processes and support systems should be streamlined to reduce burdens on both students and companies.

In conclusion, dual education has proven to be a forward-looking and mutually beneficial model. Its continued success will depend on the willingness of academic and corporate stakeholders to engage in adaptive, collaborative, and innovation-driven practices. With targeted improvements and strategic alignment, dual education can play a pivotal role in shaping a resilient and future-ready workforce.

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Screen Natives Becoming Digital Orphans: The Online Challenges of Generation Alpha

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Abstract— Background: In the digital era, the unprecedented online presence of Generation Alpha creates novel challenges related to problematic internet use. Investigating this phenomenon is essential for understanding the cognitive and social development of this cohort and for formulating effective prevention strategies. **Objective:** The aim of this study is to measure Problematic Internet Use (PIU) and its influencing and moderating factors. It also investigates the relationships between the dimensions of PIU (control, obsession, and neglect) and demographic variables among representatives of Generation Alpha. **Method:** This study employed a quantitative, cross-sectional survey design. PIU was measured using a validated, 6-item questionnaire (Problematic Internet Use questionnaire, PIU-6) on a 5-point Likert scale. A total of $N = 837$ participants were recruited from educational institutions in Fejér County, Hungary. **Results:** Based on the results, average daily internet use time is the strongest behavioral predictor of problematic internet use; however, the strength of this relationship is significantly moderated by gender and family context. The association between online screen time and PIU is significantly stronger for girls than for boys. Furthermore, the relationship between internet use time and PIU was significant for children from families with higher levels of parental education. **Conclusion:** Considering family context and gender differences is essential when evaluating the effects of online screen time, as these factors can function as either protective or risk-enhancing elements in the development of problematic internet use among Generation Alpha.

Keywords— Generation Alpha, Problematic Internet Use, Digital Well-being

I. INTRODUCTION

Generation Alpha, comprised of children born after 2010, is the first cohort to be born entirely into the digital world. For them, using technological devices is not a learned skill but an inherent one, which uniquely shapes their cognitive development, social relationships, and lifestyle[1]. However, their digital nativity not only brings advantages but also creates new types of challenges, particularly regarding internet use.

Problematic Internet Use (PIU) is a phenomenon that refers to the negative consequences of time spent in the online space[2]. The literature conceptualizes this phenomenon through three primary dimensions:

- **Control:** A diminished capacity to manage or stop internet use, often manifesting as compulsive behavior.
- **Obsession:** Preoccupation with online activities, accompanied by anxiety and withdrawal symptoms in their absence.

- **Neglect:** The neglect of essential life areas, including sleep, academic responsibilities, and social interactions, in favor of online engagement.

Active participation in the digital space also entails numerous online risk factors[3], such as excessive screen time, access to inappropriate content, cyberbullying, or social isolation. Members of Generation Alpha may be particularly vulnerable to these factors, as they are still in a critical developmental stage.

The aim of the present study is to explore the patterns of problematic internet use emerging among Generation Alpha, with a special focus on the moderating role of demographic variables. In this study, we tested two hypotheses:

H1: Average daily internet use is positively correlated with the total PIU score, particularly in the dimension of neglect.

H2: The educational attainment of parents moderates the relationship between average daily internet use and the total PIU score.

The findings of this research can contribute to the development of digital education and prevention strategies, especially within educational and family contexts.

II. LITERATURE REVIEW

A. Problematic Internet Use and Cybersecurity Risks

Members of Generation Alpha, who were born into the digital world, begin engaging with the internet at a very young age, often without parental supervision. This early and intensive online presence not only increases the risk of developing Problematic Internet Use (PIU) but also heightens their vulnerability to various cybersecurity threats.

Problematic Internet Use (PIU) encompasses a pattern of behavioral and psychological symptoms where an individual is unable to control their online activities, which become compulsive, leading to the neglect of other important life domains such as sleep, academics, or social relationships[4][5][6][7]. The three primary dimensions of PIU—control, obsession, and neglect—can contribute to an increased vulnerability to cybersecurity risks in various ways.

Impaired control, for instance, can diminish self-regulatory skills, thereby increasing a child's susceptibility to impulsive actions such as clicking on unknown links or disclosing personal information. Obsessive internet use frequently leads users to seek intense emotional stimuli, heightening the probability of exposure to hazardous or age-inappropriate materials. Finally, the dimension of neglect implies that online engagement comes at the cost of other crucial activities, thus reducing participation in offline social

interactions that could otherwise function as a protective factor for navigating the digital environment. The scope of these cybersecurity risks includes, but is not limited to, the following[8][9]:

- breaches of personal data privacy,
- cyberbullying and online harassment,
- exposure to inappropriate content,
- the formation of digital dependencies,
- vulnerability to manipulation and disinformation.

These factors can be particularly dangerous for Generation Alpha, who do not yet possess the necessary critical thinking and digital literacy to recognize and manage these threats[8]. Therefore, Problematic Internet Use and cybersecurity risks are closely intertwined, and they have a complex impact on children's psychological well-being and development.

B. Generation Alpha Characteristics and Risk Factors

Members of Generation Alpha are growing up in a technologically saturated environment that is fundamentally different from the experiences of previous generations. From a very young age, they have access to smart devices, digital content, and social platforms. Consequently, while their digital competencies develop early, their capacity for critical thinking and self-regulation is not yet fully formed[10][11][12]. The generation is characterized by a high sensitivity to multimedia content and rapid information processing; short attention spans, which reinforce the fragmented nature of content consumption; a strong visual orientation, resulting in a preference for image- and video-based content; and a form of digital socialization that often replaces or sidelines face-to-face interactions. While these characteristics are not inherently negative, they can lead to problematic behavioral patterns when combined with certain risk factors. The most common risk factors include:

- lack of parental control or excessive permissiveness regarding device use,
- a low level of digital literacy within the family context,
- unfiltered access to content, potentially leading to exposure to age-inappropriate material,
- social isolation, which prioritizes online interactions over face-to-face relationships,
- difficulties with emotional regulation, particularly in the case of withdrawal symptoms.

The patterns observed in this study indicate that members of Generation Alpha are particularly sensitive to the behavioral and psychological effects present in the online space. The risk of developing Problematic Internet Use depends not only on the amount of time spent online but also on the family, social, and educational context in which internet use occurs. The moderating role of demographic variables, such as parental educational attainment and gender, is critically important in understanding these risk patterns.

III. METHOD AND TOOLS

A. Measurement Instrument

Problematic Internet Use (PIU) was measured using the shortened Hungarian version of the Problematic Internet Use Questionnaire-Short Form (PIUQ-SF-6), a validated 6-item instrument developed by Demetrovics et al.[15]. The questionnaire assesses the phenomenon on a 5-point Likert scale across three dimensions. Two items measure the

obsession dimension (preoccupation with the internet), two items measure **neglect** (neglecting other life domains, such as academic/work performance and social relationships), and two items measure impaired **control** (loss of control over internet use, compulsive behavior). A higher total PIU score indicates an increased risk of problematic internet use. The reliability of the original scale is reported as Cronbach's $\alpha = 0.77$ [16].

To assess the internal consistency of the PIU scale and its theoretical subscales, Cronbach's alpha (α) coefficients were calculated for the Generation Alpha subsample ($N = 837$). The reliability of the total PIU scale was acceptable in this age group ($\alpha = .647$). However, the internal consistency of the impaired control ($\alpha = .238$) and neglect ($\alpha = .388$) subscales was low. Therefore, using their composite scores for further statistical analyses was deemed methodologically inappropriate for this sample; consequently, the individual items were analyzed instead. The reliability of the obsession subscale was acceptable ($\alpha = .627$).

B. Data Preparation and Analysis

Data were gathered via quantitative questionnaires administered in both paper and digital formats. Prior to analysis, the dataset was subjected to a rigorous data cleaning procedure to identify and address missing values, outliers, and data entry errors. The statistical analysis followed a multi-stage process and was executed using IBM SPSS Statistics 27, Microsoft Excel, and Python 3.11.

Initially, descriptive statistics were generated to summarize the characteristics of the sample. The internal consistency of the scales was evaluated using Cronbach's alpha, with a threshold for acceptability set at $\alpha > .60$ [13]. Relationships between variables were examined using Pearson correlation analysis. Independent samples t-tests and one-way analysis of variance (ANOVA) were utilized to test for significant differences between groups. Moderated regression analysis was employed to assess the moderating effects of key variables. The level of statistical significance was set at $p < .05$ for all analyses[14]. To explore the underlying data structure, cluster analysis was employed; the optimal number of clusters was determined using the elbow method, and the grouping was performed with the K-means algorithm.

C. Sample and Demographics

The survey included a total of $N = 837$ Generation Alpha students from Fejér County, Hungary, participating from the 5th grade of primary school and above. The gender distribution of the participants was balanced ($N = 425$, 50.8% male; $N = 412$, 49.2% female). Due to the 6-year secondary school system in Hungary, $N = 684$ (81.7%) of participants attended primary school, while $N = 153$ (18.3%) were enrolled in secondary school.

In terms of academic specialization, $N = 667$ students were in a general curriculum, $N = 101$ in a science-focused specialization (mostly math), and $N = 69$ in a humanities (mostly a foreign language). In terms of residence, the largest group consisted of students living in the county seat, where the survey was conducted (36.4%). $N = 283$ (33.8%) indicated they lived in a city, $N = 236$ (28.2%) in a village, while only 1.6% ($N = 13$) of participants were from the capital city.

Regarding family background, defined by the parents' highest level of education, the majority of parents held a

higher education diploma ($N=510$, 60.9%). A further $N=232$ had a secondary school degree, $N=65$ had a vocational qualification, and $N=30$ had a primary school education. The average daily internet use was 3.33 hours, with a large standard deviation indicating significant individual differences ($M=3.33$, $SD=2.08$).

IV. RESULTS

A. Descriptive Statistics and Correlation Analyses

The mean total score on the PIU Questionnaire was 12.33, with a large standard deviation ($M=12.33$, $SD=4.01$). A significant discrepancy was found between the items of the impaired control subscale: the mean for item PIHcontrol01 ($M=2.62$, $SD=1.05$) was considerably higher than the mean for item PIHcontrol02 ($M=1.75$, $SD=1.10$). The items of the impaired control subscale point to different levels of symptom severity. The intention to reduce use (PIHcontrol01) was a relatively common experience in the sample ($M=2.62$, $SD=1.05$). In contrast, the active concealment of use (PIHcontrol02), a more severe symptom of impaired control, occurred much less frequently ($M=1.75$, $SD=1.10$). This significant difference in the frequency of the two items explains the previously identified low internal consistency of the subscale ($\alpha=.238$).

The items of the obsession subscale had the lowest mean values, indicating that cognitive-emotional symptoms are the least characteristic for this age group. The mean for experiencing tension or restlessness while using the internet (PIHobsession01) was $M=1.92$ ($SD=1.09$), while feeling depressive or sad when unable to use the internet (PIHobsession02) was less common in the studied population ($M=1.49$, $SD=1.00$).

The neglect subscale, which measures the behavioral consequences of problematic use, showed symptoms of moderate frequency. Internet use at the expense of sleep (PIHneglect01, $M=2.26$, $SD=1.25$) and receiving signals from one's environment about excessive use (PIHneglect02, $M=2.29$, $SD=1.17$) had similar values. Overall, the most common experience was the internal intention to reduce use, followed by behavioral consequences (neglect), while the rarest were severe cognitive-emotional symptoms (concealment, withdrawal).

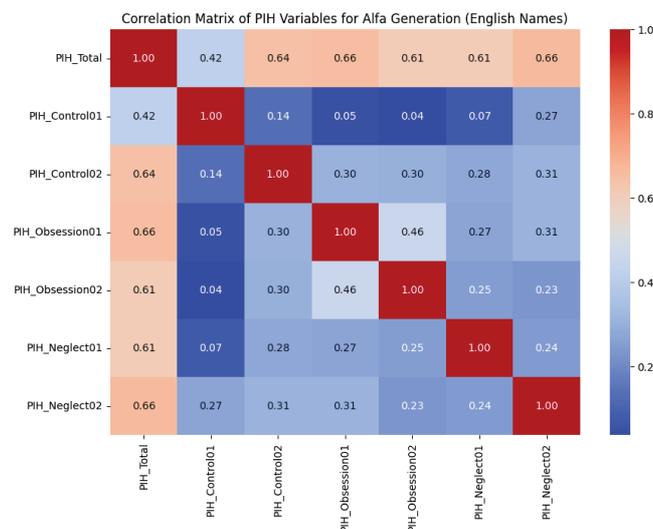


Fig. 1. Correlation matrix of the PIU items for Generation Alpha (Source: author's own compilation)

As shown in the correlation matrix of the PIU scale's internal structure in Fig. 1, each item showed a moderate to strong positive correlation with the PIH_Total score, with r_p values ranging from .42 to .66 ($p < .001$). Correlation analyses revealed several other significant relationships. The gender variable showed a weak positive correlation with both PIHcontrol01 (internal motivation to reduce internet time) ($r_p=.174$, $p < .001$) and the total PIU score ($r_p=.109$, $p < .002$). Regarding average internet time, a weak negative correlation was observed with academic specialization ($r_p = -.070$, $p = .043$), and a weak positive correlation was found with the parent's highest educational qualification ($r_p = .068$, $p = .049$). Further significant positive correlations (at $p < .001$) were found between average internet time and the following variables: concealment of internet time ($r_p = .213$), feelings of tension during internet use ($r_p = .278$), depression resulting from withdrawal ($r_p = .189$), neglect of sleep ($r_p = .492$), signals from one's environment ($r_p = .260$), and the total PIU score ($r_p = .428$). The strongest correlation was observed between average internet time and the neglect of sleep.

B. The Impact of Demographic Variables

A multiple linear regression was performed to determine the extent to which a set of demographic variables could predict composite scores of problematic internet use. The majority of demographic variables, including residence, academic specialization, and parental education, did not emerge as significant predictors. However, the overall regression model was statistically significant, $F(5, 831) = 40.87$, $p < .001$, and accounted for 19.3% of the variance in problematic internet use ($Adjusted R^2 = .193$).

Within the model, average daily internet use ($\beta = .427$, $p < .001$) and gender ($\beta = .111$, $p < .001$) were robust and significant predictors, even when controlling for other demographics. In the studied sample, problematic internet use is primarily influenced by the behavioral factor (time spent online) and gender.

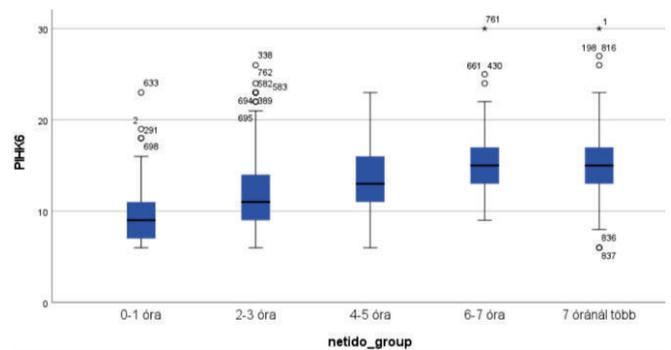


Fig. 2. Distribution of Problematic Internet Use Scores by Daily Internet Use Groups (Source: author's own compilation)

As depicted in Figure 2, the boxplot analysis revealed a dose-response relationship between daily internet use and problematic internet use scores. The results demonstrated not only progressive increases in median values across internet usage groups, but also expanding interquartile ranges, indicating greater variability in problematic internet use scores among individuals with higher usage levels.

Further analysis of individual PIU symptoms revealed that gender was a significant predictor for the desire to reduce internet time, with girls reporting higher values ($F(1, 835) = 26.22$, $p < .001$, $Adj. R^2 = .029$, $\beta = .174$,

$p < .001$). In contrast, the concealment of use, a more severe symptom, was predicted solely by average daily internet use ($F(1, 835) = 39.44, p < .001, Adj. R^2 = .045, \beta = .212, p < .001$).

Among the variables studied, feelings of tension and restlessness during internet use were associated exclusively with average daily internet use ($F(1, 835) = 69.92, p < .001, Adj. R^2 = .077, \beta = .279, p < .001$), with more time spent online predicting higher levels of tension. Similarly, feelings of sadness or depression in the absence of internet use were also associated with average daily internet use ($F(1, 835) = 29.70, p < .001, Adj. R^2 = .034, \beta = .186, p < .001$), indicating that more time online predicts more severe withdrawal symptoms..

Internet use at the expense of sleep, one of the most important signs of functional impairment, was almost exclusively associated with average daily internet use ($F(1, 835) = 266.89, p < .001, Adj. R^2 = .242, \beta = .493, p < .001$). This model had the highest R^2 value among those tested, suggesting that more time spent online is most directly and strongly reflected in the neglect of sleep. The frequency of receiving negative feedback from one's environment was also almost exclusively associated with average daily internet use ($F(1, 835) = 60.09, p < .001, Adj. R^2 = .067, \beta = .259, p < .001$), indicating that more time spent online significantly increases the likelihood that the family or the parents will signal a problem.

C. The Moderating Role of Parental Education

To test the hypothesis that parents' educational qualification influences the relationship between average daily internet use and problematic internet use, a moderation analysis was conducted using Hayes' PROCESS macro (Model 1). The full regression model was significant ($R^2 = .206, F(7, 829) = 30.78, p < .001$), explaining 20.6% of the variance in problematic internet use. The interaction between average internet time and parents' university/college education showed a significant effect ($\beta = .95, p = .015$), while the other interaction terms were not significant.

In the analysis of simple main effects by parental education level, there was no significant effect for children of parents with a primary school education ($\beta = .34, p = .307$). However, significant positive effects were found for children of parents with a vocational degree ($\beta = .83, p < .001$), a secondary school degree ($\beta = .70, p < .001$), and a higher education degree ($\beta = 1.29, p < .001$). The results support that parental educational functions as a moderator in the relationship between screen time and problematic internet use. While for children of parents with a primary school education, more time spent online is not associated with a higher risk of problematic use, this relationship is significant and strong for children of parents with higher educational attainment.

Gender also emerged as a significant moderator. The association between daily internet use and PIU was significantly more pronounced for girls ($\beta = .99, p < .001$) compared to boys ($\beta = .68, p < .001$). While increased online time elevates the risk of PIU for both genders, this dose-response relationship is demonstrably steeper for girls. This suggests that, within Generation Alpha, girls may exhibit greater vulnerability to the adverse psychological outcomes of excessive screen time, revealing a gender-specific risk profile.

D. Identification of Problematic Internet Use User Profiles

A K-means cluster analysis yielded a four-cluster solution, delineating distinct user profiles based on internet usage intensity and the psychological dimensions of PIU (control, obsession, and neglect). ANOVA tests confirmed that all clustering variables were significant differentiators ($p < .001$ for all), with average daily internet use emerging as the most potent factor for group separation ($F(3, 833) = 834.83, p < .001$).

The „**Controlled Low-Users**” ($N = 317, 37.9\%$) form the largest group, characterized by the lowest average internet use ($M = 1.7$) and the lowest scores on all symptoms of problematic internet use. They represent the „*problem-free*” profile.

The „**Intensive but Stable Users**” ($N = 203, 24.3\%$) is a group that, despite spending a lot of time online ($M = 4.8$), exhibits low PIU symptoms. They can be described as „*functional heavy-users*”, indicating that intensive use is not necessarily problematic..

The „**Ambivalent Moderate-Users**” ($N = 193, 23.1\%$) spend relatively low internet use ($M = 2.3$) but scored relatively high on the intention to reduce use ($M = 3.0$) and on receiving negative feedback from others ($M = 3.0$). This suggests a perceived problem or conflict with their use despite its moderate level.

The „**Problematic Intensive-Users**” ($N = 124, 14.8\%$) spend the most time online ($M = 6.5$). This was the smallest but most at-risk segment. This cluster was defined by the highest overall PIU scores, especially regarding the neglect of tasks and sleep ($M = 4.0$), alongside high levels of impaired control and obsession, marking them as the most vulnerable group.

The results highlight that within Generation Alpha, problematic internet use is not a homogeneous phenomenon but rather manifests in several distinct patterns.

V. DISCUSSION

The primary objective of this study was to analyze the patterns of Problematic Internet Use (PIU) within a sample of Generation Alpha from Fejér County, Hungary, focusing specifically on the impact mechanisms of screen time, demographic variables, and parental factors. Our findings reveal that the most prevalent symptoms of PIU are linked to the behavioral dimension of neglect. Excessive internet use at the expense of sleep was the most commonly reported issue, though it often co-occurred with a stated internal desire to reduce use. The incidence of significant cognitive-emotional symptoms was notably lower in our sample. A comprehensive assessment indicates that problematic internet use within this age cohort is predominantly functional in character, primarily manifesting through the disruption of daily behavioral patterns and routines.

The results clearly support Hypothesis 1, showing that online screen time is indeed most strongly associated with neglect. The correlation analysis revealed the strongest relationship ($r_p = .492$) between average daily internet use and the neglect of sleep. This finding is consistent with international literature, which consistently demonstrates a negative relationship between screen time, excessive online presence, and sleep problems (shorter sleep duration, poorer sleep quality, difficulty falling asleep) in adolescents. For

instance, in Hungary, boys who are intensive social media users were 85% more likely to report sleep disorders[17][18]. The neglect of sleep is a form of functional impairment, and its negative consequences include a decline in academic performance, the perpetuation of PIU, and the development of mental health problems[19].

The results also confirmed Hypothesis 2, showing that gender and parental education significantly moderate the relationship between internet time and PIU. The moderation analysis revealed complex patterns in the effect of parental education. For children of parents with higher education degree, online screen time significantly and strongly increased the risk of PIU, whereas this moderating effect was not detected for children of parents with a primary school education. This finding aligns with the research of Livingstone and Helsper[20], who pointed out that parental mediation strategies—including active co-use and setting interaction rules—are not always effective in reducing online risks. The increased vulnerability to PIU among children of higher-educated parents, despite their parents' mediation practices, suggests that conscious parental intervention alone does not guarantee effective protection.

In the examination of gender as a moderating variable, the relationship between screen time and PIU was found to be significantly stronger among girls. This contrasts with some earlier research that identified boys as the higher-risk group, particularly concerning online gaming, academic performance, and a lack of self-control[21][22]. While online screen time increases the risk of PIU for both genders, this association is notably stronger for girls, indicating their heightened vulnerability to the negative effects of excessive screen use (anxiety, depression, psychological distress) [23][24].

Overall, the findings indicate that problematic internet use is not exclusively a function of the quantity of screen time. A comprehensive understanding of the phenomenon requires the simultaneous examination of the context of use, gender differences, and the complex influencing role of family background.

A. Limitations and Future Directions

The primary limitation of this study is the occasional low reliability of the subscales of the problematic internet use instrument, which necessitates caution when generalizing the results. The lack of reliable and valid measurement tools for Generation Alpha represents a broader challenge in the field.

An additional constraint was the use of a self-report methodology, which introduces the potential for response biases. Self-reported data are vulnerable to distortions arising from social desirability and recall inaccuracies, especially concerning the estimation of time spent online. These methodological limitations delineate several key avenues for future research, including the implementation of longitudinal study designs and, crucially, the development of novel, reliable, and valid instruments specifically designed and validated for the unique characteristics and online behaviors of Generation Alpha.

VI. SUMMARY

The present research examined the phenomenon of Problematic Internet Use (PIU) within Generation Alpha, with a focus on its associations with internet time use, demographic factors (gender, parental education), and psychological

profiles. The study utilized a cross-sectional design, with a sample of 837 students in upper primary and secondary education in Fejér County, Hungary, completing a survey. Data were analyzed via correlation, regression, moderation, and cluster analyses.

Findings indicated that average daily internet use ($M = 3.33$ hours) was most strongly correlated with sleep neglect ($r_p = .492, p < .001$). A regression model accounted for 19.3% of the variance in PIU, with screen time ($\beta = .427$) and gender ($\beta = .111$) being the most potent predictors. Moderation analyses demonstrated that the association between online screen time and PIU was significantly more pronounced for girls and for children with higher-educated parents. A key finding from the cluster analysis, which identified four distinct user profiles, was that screen time is not a sufficient standalone indicator of problematic use. For instance, the „intensive but stable users” (24.3%) reported high online screen time without problematic symptoms, while the „ambivalent moderate-users” (23.1%) exhibited signs of impaired control at lower levels of use.

This study demonstrates that PIU in Generation Alpha is a complex, multifactorial construct that cannot be defined solely by the quantity of screen time. The results confirm the central role of behavioral neglect and show that risk profiles are considerably shaped by demographic context and usage patterns. The research underscores the necessity of longitudinal studies and the development of validated, age-appropriate assessment instruments.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used Gemini 2.5 Pro in order to improve the language and readability of the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Teacher motivation in engineering education

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Abstract—The quality and effectiveness of engineering education is closely linked to the professional commitment and motivation of teachers. The aim of this study is to explore the main factors influencing teacher motivation in the context of higher education engineering training, regarding the challenges and opportunities associated with the transformation of the role of teachers. Through a review of the literature, we analyzed domestic and international sources to identify the internal and external components of motivation and their impact on teaching performance, innovation, and student achievement. The study highlights that professional autonomy, positive feedback, a sense of purpose in teaching, and institutional support plays a key role in maintaining motivation. The study can contribute to the development of engineering education by providing guidance for the development of institutional strategies to support teacher motivation.

Keywords—engineering education, motivation of teachers, literature review, innovation, student achievement

I. INTRODUCTION

Technological advancements, particularly the rapid rise of artificial intelligence (AI) is fundamentally reshaping the landscape of education. As AI tools become increasingly integrated into teaching and learning environments, a key challenge emerges: how can educators not only keep pace with these changes but also ensure that students engage meaningfully with the learning process, rather than passively consuming AI-generated content?

In engineering education, where independent problem-solving and deep understanding are essential, it is especially important that students complete tasks autonomously and with comprehension. This depth of learning is closely tied to one of the most critical factors in education: motivation, which significantly influences both student and teacher performance [1]. A motivated teacher can inspire, guide, and support students effectively, while a lack of motivation can undermine the quality of instruction and diminish student engagement. An unmotivated educator is unable to foster a dynamic and responsive learning environment, which is particularly detrimental in a field as demanding and evolving as engineering.

With the rapid development of IT and AI technologies, it is essential that educators continuously develop their own professional competencies. However, regardless of age or experience, learning and development are only sustainable when driven by adequate internal or external motivation [2]. Therefore, understanding and supporting teacher motivation is a key element in maintaining the quality and relevance of engineering education in the 21st century.

II. THE CONCEPT AND TYPES OF TEACHER MOTIVATION

Motivation plays a key role in education, as it determines teachers' attitudes towards teaching, their professional

development, and their impact on students. Teacher motivation is the sum of internal and external factors that encourage teachers to perform their work actively, with commitment and effectively. Teacher motivation not only influences the quality of education, but also indirectly influences students' attitudes toward the subject and its effectiveness.

We distinguish between two basic types of motivation:

- **Internal motivation:** The instructor is driven by their own interests, values, professional curiosity, and desire for self-fulfillment. With this type of motivation, the instructor finds joy in teaching, sharing knowledge, and professional development. Intrinsic motivation is particularly important for long-term commitment and the development of creative, innovative teaching practices.
- **External motivation:** The teacher is motivated by external factors such as financial rewards, recognition, career opportunities, or institutional expectations. Although external motivation can contribute to performance, it is rarely sufficient on its own to maintain long-term professional commitment.

For effective teaching, it is important that educators have a balanced motivation, with internal motivation predominating. The emergence of artificial intelligence in education creates new challenges and opportunities, and adapting to these also requires motivation – both in terms of learning and in terms of renewing teaching methods.

III. MOTIVATION THEORIES

Motivational theories help us understand what internal and external factors motivate individuals to learn, work, and achieve self-actualization. In this study, we present four classic motivational theories that are relevant to the higher education environment, which we will later reflect on with reference to the literature.

A. Deci–Ryan theory (self-determination theory)

The self-determination theory (SDT) developed by Deci and Ryan [3] is based on the internal nature of human motivation and identifies three universal, innate psychological needs: competence, autonomy, and relatedness. According to the theory, we are motivated, productive, and satisfied when these needs are met.

- **Competence** refers to the need for individuals to be able to function effectively and efficiently in their environment.
- **Autonomy** expresses the desire for independence, i.e., the ability to act based on one's own decisions.
- **Relatedness** refers to the need for human relationships and belonging to a community.

The central tenet of the theory is that people are inherently motivated to develop, act independently, and form relationships. When these internal motivational factors are supported, for example, in a supportive educational environment, individuals are capable of higher levels of performance, creativity, and personal fulfillment.

Several international studies provide examples of this. For example, Taylor et al. [4] conducted a lengthy study examining the effect of different types of motivation on school performance. According to the results, intrinsic motivation was the only form of motivation that was consistently positively related to school performance, and intrinsic motivation reduced lack of motivation and increased active participation in the learning process. These results have been confirmed in different cultural contexts (e.g., Canada, Sweden).

In their 2016 article, Froiland & Worrell [5] examined a diverse high school sample (N = 1,575) where, according to their research, intrinsic motivation indirectly influenced academic performance through classroom engagement. The model explained 75% of the variance in classroom engagement and 33% of the variance in grade point average (GPA). The results were replicable across different ethnic groups (e.g., African American, Hispanic students), making them culturally reliable.

B. Herzberg's two-factor theory of motivation

Frederick Herzberg, an industrial psychologist, developed his two-factor theory of motivation in the 1950s [6] which is often referred to as the motivation-hygiene theory. The theory is based on the idea that employee satisfaction and motivation are influenced by two separate groups of factors: hygiene factors and motivational factors. According to Herzberg, these are not opposites but represent separate dimensions and have different effects on work performance.

Hygiene factors are basic conditions whose absence causes dissatisfaction, but whose presence alone does not motivate. These factors are related to the work environment, for example:

- working conditions,
- salary,
- job security,
- company regulations,
- relationships with managers and colleagues,
- status.

In higher education, these factors appear in the form of institutional infrastructure, stable employment, remuneration, and administrative support for teachers, for example. Although these do not directly encourage teaching creativity or commitment, their absence can cause significant frustration and burnout.

In contrast, motivational factors are those that elicit genuine internal satisfaction and commitment. These include, for example:

- recognition,
- performance,
- opportunities for advancement,
- responsibility,
- personal development,
- the content of the work.

In higher education, these factors are particularly important in maintaining the professional motivation of teachers. Teachers feel motivated when they consider their

work valuable, have opportunities for professional development, research, and publication, and are given autonomy in choosing teaching methods.

Herzberg's model is therefore well suited to examining teacher motivation, especially in an educational environment transformed by artificial intelligence, where the introduction of new technologies creates new challenges and opportunities. The use of AI tools, for example, can increase opportunities for responsibility and personal development, but it can also introduce new hygiene factors, such as data security or lack of technical support.

Herzberg's theory is based on the following assumptions:

- Motivation is not a one-dimensional process. Motivation does not simply work along the lines of reward or punishment, but as a complex, multi-factor system.
- Money alone is not enough for long-term motivation. Although salary is important, it cannot sustain internal commitment in the long term.
- There are basic and higher-order work-related needs. Employees seek not only security and stability, but also meaning, development, and recognition.
- People have an intrinsic need for growth and self-actualization. Learning, development, and responsibility serve as internal sources of motivation.
- Work must be more than just a means of earning money. Work becomes motivating when it provides meaning, purpose, and opportunity for the individual.

In their quantitative study, Ibrahim et al. [6] applied Herzberg's theory to examine motivation in language learning. The results show that authentic teaching materials, relevant tasks, and teacher recognition significantly increase student motivation, acting as motivators. In contrast, exams, homework, and a lack of teacher organization, as hygiene factors, cause dissatisfaction. The research confirms that the Herzberg model is well suited to understanding and developing student motivation in an educational setting.

In his study, Akdemir [7] examined the motivation of 463 teachers based on the components of Herzberg's theory. The results showed that teachers' motivation levels were above average, especially among female teachers. Interestingly, motivation did not depend on the type of school or the teachers' qualifications. The research supports the idea that Herzberg's internal and external motivational factors are well suited to measuring and interpreting teacher motivation.

Escollada [10] examined the effect of motivators (e.g., recognition, responsibility) and hygiene factors (e.g., salary, working conditions) on teacher satisfaction and performance among teachers in the Philippines. The results showed that motivators had a stronger influence on teacher satisfaction than hygiene factors. Teacher satisfaction had a positive effect on student performance and the quality of the learning environment. The research recommends supporting the professional development of teachers.

C. Application of Maslow's hierarchy of needs in higher education

In 1943, American psychologist Abraham Maslow published his theory of the hierarchy of needs [9] which became one of the fundamental models of motivation research. According to this theory, human needs are arranged

hierarchically, and an individual's behavior is motivated by their currently unmet needs. The most well-known representation of this model is Maslow's pyramid, which distinguishes between five levels, from basic physiological needs to self-actualization.

1. **Physiological needs:** The base of the pyramid consists of the basic needs necessary for survival: food, water, sleep, and health. In higher education, these factors indirectly influence students' learning ability, for example, a lack of proper nutrition, rest, and health can reduce concentration and performance.
2. **Safety needs:** The next level is the need for physical and psychological safety. For students, this can mean institutional stability, a predictable study system, financial security (scholarships, grants), and a supportive educational environment. For teachers, this includes job security, contractual conditions, and institutional support.
3. **Social needs:** Humans are social beings, so relationships, community experiences, and a sense of belonging are fundamental motivational factors. In higher education, this manifests itself in student communities, group work, mentoring programs, and teacher-student interactions. For teachers, belonging to professional communities, collaborating with colleagues, and a supportive atmosphere have a motivating effect.
4. **Need for recognition:** The fourth level is the need for self-esteem and social recognition. Students are more motivated when their performance is recognized, they receive feedback. For teachers, recognition can take the form of professional awards, publication opportunities, promotion, or positive student feedback.
5. **Self-actualization:** At the top of the pyramid is self-actualization, which is the individual's inner drive to develop their abilities and talents to the fullest. This is particularly important in higher education: students feel motivated when they have the opportunity for creative, independent thinking, research, and problem solving. For educators, self-actualization manifests itself in the freedom to teach, engage in research, and pursue professional development.

Maslow's theory is therefore well suited to education, particularly in understanding student and teacher motivation. AI-based educational environments create new opportunities for self-actualization, but they also pose challenges in maintaining lower-level needs such as security and social connections.

In her study, Nóra Katona [11] provides a theoretical synthesis of the motivational model of self-regulated learning, which is based on Maslow's theory of self-actualization. The author points out that personality development, value orientations, and intrinsic motivation play a key role in the learning process. The levels of Maslow's pyramid (physiological, safety, social, esteem, and self-actualization) have a complex effect on learning and teaching: higher-level motivations, such as self-actualization, are only activated when lower levels are satisfied. Teachers' motivational styles and goal orientations directly influence how they plan and evaluate learning processes, thereby also affecting student development.

In contrast, Gabriella Pusztai [12] examined the role of Maslow's pyramid of motivational factors in the professional activities of teachers in an empirical study. Based on the analysis of 24 teacher interviews, she concluded that intrinsic (internal) motivational factors (such as self-actualization, professional autonomy, and creativity) play a decisive role in making a teacher innovative. The needs associated with the higher levels of Maslow's pyramid, especially self-esteem and self-actualization, act as incentives for the development of educational innovations. Based on the interviews, teachers make effective professional decisions when their motivational base is stable and when they have opportunities for professional development and recognition. At the same time, some motivational factors can also act as obstacles, especially when lower-level needs, such as job security, are not satisfied.

D. McClelland's theory

In the 1960s, American psychologist David C. McClelland developed a theory of human motivational needs [13], according to which human behavior is determined by three learned motivational needs: the desire for achievement, relationships, and power. The basic premise of the theory is that these needs are not innate but develop through an individual's cultural environment and life experiences and can be measured and developed through targeted programs.

According to McClelland, all three needs are present in every person, but in different proportions, and the dominant need fundamentally determines an individual's behavior, decisions, and career choices.

1. **Need for Achievement (nAch):** Individuals with a dominant need for achievement are highly motivated to perform well. In higher education, these individuals perform well in independent research tasks and competitive situations and are motivated to excel in their work. They are characterized by:
 - seeking challenging tasks,
 - an attraction to measurable goals,
 - preferring personal responsibility,
 - need for feedback and success.
2. **Need for Affiliation (nAff):** For people of this type, establishing and maintaining social relationships is the most important thing. In higher education, these individuals work well in teams and project-based learning, and a supportive working environment is important to them. Their characteristics are:
 - desire to belong to a group,
 - search for acceptance,
 - avoidance of conflict,
 - preference for cooperation.
3. **Need for power (nPow):** These individuals are motivated to influence and control others. In higher education, these individuals often take on leadership roles in student organizations, mentoring programs, or later pursue leadership careers. Their characteristics include:
 - seeking leadership roles,
 - preferring decision-making situations,
 - need for status and recognition,
 - striving to increase organizational influence.

McClelland's theory is particularly useful in organizational practice, as it helps to map individuals' motivational profiles and thus tailor jobs, tasks, and development programs to them. Applied in higher education,

it can help identify the motivational types of teachers and students and optimize the learning environment.

The results of motivation research clearly show that there is no universal motivation model that can be applied in all situations. Individuals' motivation patterns vary significantly, influenced by personal characteristics, cultural background, and workplace environment. As a result, modern organizations are increasingly using complex and flexible motivational strategies that consider individuals' dominant needs, development directions, and the dynamics of the work environment. A personalized approach not only serves to increase performance but also contributes to the long-term maintenance of employee satisfaction and commitment.

In his empirical research, Ónodi [1] analyzed 3,305 student opinions from Corvinus University of Budapest between 2017 and 2023. The methodology of the study consisted of K-means cluster analysis, questionnaire-based data collection, and open-ended questions. The research focused on students' attitudes and motivation, with particular emphasis on how this influences their assessment of the subject taught by their instructors. Based on the results, internal motivational factors, such as the desire for knowledge and the need for development play a dominant role, but external reinforcements (e.g., recognition, grades) also have a significant impact. The research highlighted that teachers' motivation and methodological openness have a direct impact on student satisfaction, which in turn affects teacher performance evaluations. The motivational dimensions examined, performance, power (e.g., instructor influence, recognition), and affiliation (e.g., instructor-student relationship), are closely aligned with McClelland's three-need theory. The motivational profile of teachers can be interpreted along these three main motives, which significantly influence teaching effectiveness, willingness to innovate, and the quality of the learning environment.

The study by Rybnicek, Bergner, and Gutschelhofer [14] involved 44 participants and aimed to validate McClelland's need theory in a modern work environment using a new neuropsychological methodological approach. During the study, participants received different types of rewards (e.g., high income, respectful leadership, prestigious company car) while their brain activity was measured using fMRI. The results showed that different rewards activated different areas of the brain, corresponding to the participants' dominant motivational needs. A close match between the reward and personal needs resulted in stronger neural activation in the reward system (e.g., putamen, caudate). The research confirmed that personalized motivational strategies can be more effective than uniform reward systems. Although the study did not specifically target educators, the results are directly applicable to the higher education setting. Teachers' motivational profiles, such as performance-oriented or relationship-oriented attitudes, can influence how they respond to different forms of recognition. The study supports the idea that professional feedback and development opportunities that match motivational needs can increase teacher commitment and performance.

IV. CHALLENGES AND MOTIVATIONAL FACTORS IN ENGINEERING EDUCATION

A. Pedagogical and professional challenges of engineering education

Engineering education holds a unique position within technical higher education, as it must simultaneously meet the demands of scientific rigor and practical relevance. The goal is not only to transmit theoretical knowledge but also to cultivate problem-solving abilities, systems thinking, and innovation skills.

Rapid technological advancements, particularly in areas such as artificial intelligence, automation, and digital design, pose continuous challenges for educators. Instructors must not only keep their professional expertise up to date but also adapt and evolve their teaching methodologies to align with the changing industrial landscape.

Project-based learning, laboratory work, and assignments rooted in real-world industrial problems play a central role in engineering education. These approaches not only help develop professional competencies but also enhance student motivation, especially when tasks are challenging and clearly connected to future workplace scenarios [15].

A major pedagogical challenge is the diversity in students' prior knowledge and learning experiences. While some arrive with strong foundations in mathematics and logical reasoning, others struggle with abstract thinking or technical language. Moreover, many students lack effective learning strategies, as their previous educational environments may not have required independent study, structured work habits, or deep conceptual understanding.

Supporting the development of these skills during university studies is essential. This requires intentional pedagogical support, differentiated instructional methods, and considerable patience from educators [16]. Addressing learning difficulties, sustaining motivation, and guiding individual learning paths are among the most complex tasks in engineering education. These responsibilities demand not only subject-matter expertise but also psychological insight and pedagogical sensitivity from instructors.

The role of teachers in engineering education has undergone significant changes in recent decades. Teachers are no longer just knowledge transferers, but also mentors, facilitators, and professional partners. The rise of digital tools, AI-based learning environments, and online platforms requires new competencies from teachers: technological proficiency, digital pedagogical sensitivity, and flexible learning organization skills.

B. Motivational factors in engineering education

Motivation plays a central role in the professional engagement of university instructors working in engineering education. In a constantly evolving technological environment, educators are expected to remain adaptable, innovative, and committed to both their academic discipline and their students. Their motivation is shaped by a combination of internal and external factors, which together influence their effectiveness, creativity, and long-term dedication.

Internal motivation, such as the pursuit of professional growth, the satisfaction of contributing to student development, and the personal fulfillment derived from

teaching, is essential for fostering innovation and resilience. At the same time, external motivators, including institutional recognition, access to research opportunities, and prospects for career advancement, also play a significant role in maintaining sustained engagement.

The motivational dynamics of engineering educators can be understood through McClelland's three-need theory [13], which identifies achievement, power, and affiliation as fundamental psychological needs. These needs are reflected in various aspects of academic life. Professional autonomy, for example, is a key motivational factor that allows educators to design their own teaching methods, select course content, and determine assessment strategies. This autonomy supports the need for achievement by enabling instructors to pursue excellence and implement their pedagogical vision. Recognition from students, colleagues, or institutional leadership reinforces the need for power by enhancing the educator's influence and status within the academic community.

Institutional support is also a decisive factor in shaping motivation. When universities provide access to modern infrastructure, professional development programs, and opportunities for research and innovation, they help satisfy both achievement and power needs. Such support encourages educators to experiment with new approaches, engage in continuous learning, and contribute to the advancement of educational practices. These opportunities also promote self-actualization, which is a deeper form of intrinsic motivation and a key element of long-term professional fulfillment.

Student feedback contributes significantly to teacher motivation. When feedback is constructive and focused on development, it offers valuable insights into the effectiveness of teaching and strengthens the sense of affiliation by fostering a feeling of connection and shared purpose. Furthermore, when educators witness the long-term impact of their work on students' professional growth and success, it reinforces the meaning of teaching and strengthens their professional identity.

In summary, the motivation of engineering educators is shaped by a complex interplay of personal aspirations, institutional conditions, and interpersonal relationships. Supporting these motivational factors is essential for fostering innovation, maintaining commitment, and ensuring the continued excellence of engineering education.

C. Balancing Quality, Retention, and Evaluation in Higher Education

University lecturers today work under considerable pressure, particularly due to the problem of student dropout rates in higher education institutions. The primary goal of lecturers is to minimize dropout rates while ensuring high-quality education and the transfer of relevant, applicable knowledge to students. Although the educational process is influenced by several other factors, this analysis does not discuss them in detail.

The system of performance-based evaluation of teachers has been at the center of higher education discourse since the early 2000s [1]. At the end of each semester, students are regularly asked to evaluate the work of their teachers. The questionnaires measure teacher performance on a scale of 1 to 5, where 1 is the lowest and 5 is the highest rating. However, this feedback mechanism can also be interpreted as a form of

external pressure on teachers, as the evaluations can affect their professional reputation and career advancement.

Lantos Ránki [17] points out that "students are happy to learn when teachers are happy to teach". This statement emphasizes that the motivation and professional satisfaction of teachers has a direct impact on students' willingness to learn. Encouraging teachers, especially in the direction of lifelong learning and methodological renewal, is essential for maintaining quality education. The attention and interest of students and effective cooperation between teachers and students are among the most important sources of teacher satisfaction.

The learning environment, the teaching methods used, the nature of the curriculum, and the personality of the teacher all play a key role in motivating students. At the same time, research also shows that student evaluations can be distorted, especially in cases where students are dissatisfied with their own performance or have not put enough energy into their studies yet still expect high scores. Therefore, student feedback should be treated with caution when evaluating instructor performance, considering the subjective factors that may distort the evaluation.

Another challenge for teachers is that the primary and secondary education system has undergone significant changes in recent years. Students entering higher education often come from difficult family backgrounds and have different skill sets than in the past. In addition, the number of students requiring special treatment is also increasing in higher education, which requires special attention from teachers. As a result, teachers need to pay increased attention to teaching learning techniques, such as developing note-taking skills. With the spread of the digital environment, reading comprehension problems are becoming more common, which are already being noticed in primary education and are being addressed with targeted programs.

V. CONCLUSIONS

The aim of our research was to explore the role of motivation in education, with particular emphasis on the higher education environment. Based on an analysis of previous studies, we examined internal and external motivational factors, as well as four classic motivational theories (Maslow, Herzberg, Deci-Ryan, McClelland), which we associated with relevant empirical and theoretical research.

Based on the results of the study, it can be concluded that both internal and external motivation are essential for educators to be able to perform their educational tasks in an authentic, up-to-date, and high-quality manner. The role of internal motivation is particularly important, as it ensures long-term commitment, professional development, and a willingness to innovate. Herzberg's two-factor model is still relevant today, as it points out that financial rewards alone are not sufficient to maintain long-term employee motivation and that work has a deeper, personal significance for the individual.

A lack of motivation can lead to burnout, which jeopardizes not only teaching performance but also, indirectly, student achievement. University management has recognized this risk, and in recent years there has been a growing number of institutional initiatives aimed at strengthening external motivational factors. These include forms of professional recognition, research and continuing education opportunities,

and institutional practices that support faculty autonomy. These initiatives contribute to ensuring that faculty members have an appropriate working environment that supports professional fulfillment and prevents burnout.

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Educational material quality evaluation using text analysis in Python

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Abstract— The study aims to evaluate educational material using modern text processing and analysis methods. The work helps determine how easily students understand the text, its structure, the use of difficult-to-understand terms, and more. Analyzing the educational material facilitates decisions on the feasibility of publishing new student textbooks.

Keywords— text quality evaluation, text processing, educational material analysis methods

I. INTRODUCTION

Digital transformation is gradually permeating virtually every aspect of our lives. Significant changes leading to the transition from third-generation industry to Industry 4.0 involve the use of advanced technologies such as the Internet of Things, artificial intelligence, big data, automation, and the digitalization of various processes.

II. MODERN CONDITIONS IN EDUCATION DEVELOPMENT

A. New Challenges in Education

Industry 4.0 and the digitalization of higher education offer numerous opportunities for the development and improvement of educational processes [1 - 4]. They stimulate changes in approaches to teaching, opening up new formats and resources for student learning. However, the key is the ability to adapt to a rapidly changing world and utilize advanced technologies to achieve better results. To harness this potential, universities are shifting their focus to student participation and independent research. These processes are constantly interacting with each other and with the environment. It creates new challenges, such as the development of relevant curricula that meet student needs and the demands of the modern labour market [5 - 9]. The digitalization of education also raises issues of data security and privacy, the need to develop information literacy, and copyright compliance.

In these conditions a huge amount of new methodological material in various formats is emerging. The problem of assessing the quality of methodological materials has long been relevant. There are well-known methods for determining the quality of such materials. These are primarily expert assessments that take into account the inclusion of topics in methodological materials that meet the requirements of the Federal State Educational Standard (FSES) and educational programs. Educational and methodological literature is created by people, and their views may be biased, perhaps focusing on only one scientific school, or may become outdated, etc.

Currently, there is no clear concept for determining the impact of the quality of methodological materials on the

development of competencies and, consequently, on the quality of education especially in Russia.

So, education quality assessment also requires revision and a new approach, taking these challenges into account.

B. New Concept of Education

One of the main challenges in assessing the quality of higher education is the changing concept of education itself. Today, education is no longer limited to simply imparting knowledge and skills. It must shape individuals' personalities, develop critical thinking, and foster social and communication skills.

Tools such as cloud services, video conferencing, and digital libraries have become available, enabling remote learning and work, reducing the need for students and faculty to be present in a single physical location. Furthermore, digital technologies offer new learning formats based on interactivity, individualized approaches, and autonomy student work.

There are various concepts for assessing the quality of education, but there is currently no review of the relevant approaches that address the impact of the quality of methodological materials on the development of competencies and, accordingly, on the quality of education in the context of digital transformation.

III. NATURAL LANGUAGE PROCESSING

Analysing educational material requires the use of modern models and technologies. This study requires processing and analysing large volumes of text data, which requires the use of NLP. Numerous text generation tools, such as OpenAI's ChatGPT, rely on NLP. Natural language processing models consist of two components: training data and specialized algorithms [10, 11]. The process of analyzing teaching materials involves several stages:

A. The first stage

First, the data must be cleaned of unnecessary or duplicate information [12, 13, 14]. The more contaminated the data, the more difficult it will be for the model to understand what is important and what is not. Therefore, it is necessary to remove duplicates, convert strings to the same case, and remove unnecessary characters.

B. Tokenization

Next is a tokenization step. To enable the model to process text at the semantic level, the cleaned data was broken down into individual units—tokens [12, 13, 14]. In this study, tokens are represented by words. In the future, we plan to use other token types: symbols, phrases, and other elements, depending

on the task and context. An example of tokenization is dividing text into individual words:

“Education is important” → [Education, is, important]

Tokenization allows to transform text into a structured representation used for further analysis or processing. Russian and many other languages have suffixes that change the form of a word but not its meaning. To avoid confusing the program, words had to be converted to their dictionary form—a lemma—by performing lemmatization.

Stemming is also a similar process where the root of a word is extracted. Lemmatization and stemming improve the efficiency of text processing by reducing the number of unique tokens. The model will run faster, and less memory will be required to store words.

C. . Data labeling and creating a dataset

The next step is data labelling. Each document, text fragment, or word—that is, each token—must be assigned a label that describes the object in question [12, 13, 14]. The format and content of the label depend on the task at hand.

Another step is creating a dataset. Before training the model, the labelled data must be transformed into a dataset—that is, structured. The dataset is a table of tokens with their relevant features and labels. For text data in this study, it is stored in CSV format.

Word embedding is also possible for data presentation.

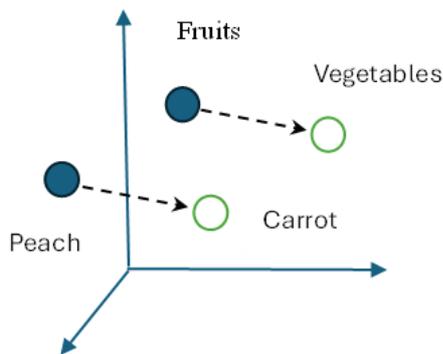


Fig. 1. Example of word embedding

D. Data Vectorization

Machine learning models can’t handle text data; they only understand numbers. Therefore, data scientists need to translate tokens into a set of numerical values.

There are different approaches to this.

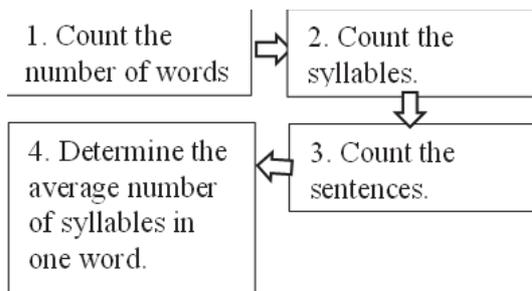


Fig. 2. Algorithm

The two most popular are bag-of-words and N-grams.

Bag-of-words simply encodes tokens into numbers, accounting for their quantity but ignoring context and specific order.

When using N-grams, words are encoded not one at a time, but two or three at a time. This preserves the structure of sentences and their context.

Notes.

Individual words, words with an apostrophe, abbreviations, numbers, symbols, and combinations of symbols are counted as units.

Count syllables in words, and count abbreviations, numbers, symbols and their combinations as monosyllabic words.

Each complete speech phrase separated by a period, colon, semicolon, question mark, exclamation mark, or dash is considered one sentence.

IV. WEB SERVICE DEVELOPMENT

A web service based on large-scale language models (LLM) was developed for the automatic analysis of educational publications using artificial intelligence. The system executes comprehensive processing of text materials, including content complexity assessment, structural analysis, logical consistency checking, and identification of semantic relationships between thematic blocks.

The service allows to download educational materials in PDF format and receive a detailed content analysis.

A. Technologies:

- Backend: Quart (asynchronous version of Flask).
- Interface: HTML/CSS.
- ML methods: textstat, TF-IDF, BART, BERT.

B. Requirements:

- OS: Windows 10/11 (64-bit).
- RAM: 8 GB (16 GB recommended for large texts).
- Python: not less than 3.9.
- Video card: NVIDIA (preferred for BERT acceleration).
- Analysis file format: PDF.
- Maximum file size: up to 10 MB.
- Processing time for one file: approximately 1.5 - 2 minutes.

C. Web Service Exploitation

The web service exploitation is simple:

Download the PDF file of the textbook using the download button on the main page, → Click the "Check" button. → Wait 1.5 to 2 minutes for the service to process the file. → Once the analysis is complete, we will receive a report with the results.

The page with results is presented on Fig. 3.

The first block is readability in percentage.



Fig. 3. The page with results

The second is coherence (from the Latin *cohaerens* - "being in connection") – in linguistics, "the integrity of a text, consisting of the logical-semantic, grammatical and stylistic correlation and interdependence of its constituent elements (words, sentences, etc.); one of the defining characteristics of a text/discourse and one of the necessary conditions of textuality.

The third one checks whether the text structure complies with standards.

The fourth block allows to determine a text style.

There are the details of the text analysis in fifth block: Flash index, number of sentences, number of words, number of syllables and text complexity.

The service selects keywords automatically (sixth block).

After the analysis, a set of recommendations (seventh block) for improving the text of the educational material is formed.

CONCLUSION

With the growing volume of educational literature from Russian authors, the developed software reduces the workload of staff involved in selecting materials for students. This web service helps automate the process of analysing educational materials at the university. While existing text analysis tools exist in European languages, the development takes into account such specific features as working with Russian-language text, which differs in structure and word formation. This service is also integrated into the university's system for accepting educational materials for publication, making the web service relevant and in demand. Future plans include expanding the service's functionality, refining its algorithms, and incorporating fuzzy models to improve analysis.

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Measuring Text Similarity in Engineering Students' Technical Reports: A Cosine Similarity-Based Approach for Plagiarism Detection

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Abstract—In engineering education, detecting plagiarism in technical reports is a significant challenge for instructors, particularly in large cohorts where manual comparison is impractical. This paper presents an automated, open-source tool designed to measure text similarity in students' technical reports using Term Frequency-Inverse Document Frequency (TF-IDF) vectorization and cosine similarity. The tool generates a similarity matrix, identifies documents exceeding a customizable 65% threshold, and provides detailed outputs for instructor review. By facilitating similarity detection, the tool promotes independent technical writing, a critical skill for future engineers. Evaluation on a dataset of engineering reports demonstrates its effectiveness, with results displayed in a user-friendly graphical user interface (GUI) and text reports. The tool's scalability and adaptability make it suitable for technical disciplines, including geoinformatics. Limitations, such as handling semantic paraphrasing, and future enhancements, such as integrating optical character recognition (OCR), are discussed.

Index Terms—Plagiarism Detection, Cosine Similarity, TF-IDF, Technical Writing, Engineering Education, Text Similarity

I. INTRODUCTION

Technical writing is a cornerstone of engineering education, enabling students to articulate complex designs, analyses, and solutions with clarity and precision. Independent report writing fosters critical thinking, problem-solving, and professional communication, skills essential for future engineers. However, plagiarism undermines these educational objectives by preventing students from engaging deeply with technical content. In large cohorts, manually comparing submissions is infeasible, and the structured nature of technical reports—replete with domain-specific terminology—complicates distinguishing legitimate similarities (e.g., shared technical terms) from plagiarism (e.g., copied or paraphrased content). This challenge is particularly pronounced in disciplines like geoinformatics, where reports often describe standardized processes, such as digital camera calibration or point cloud modeling, leading to inherent similarities [5], [6].

The consequences of plagiarism extend beyond academia, impacting the engineering profession where originality and ethical conduct are paramount. For instance, in industry, copied or inadequately documented technical reports can lead to design flaws, safety risks, or legal disputes. At Óbuda

University's Alba Regia Faculty, geoinformatics courses emphasize independent report writing to prepare students for real-world challenges, such as developing geospatial algorithms or analyzing 3D models [4]. However, the high volume of submissions in such courses necessitates automated tools to ensure academic integrity while maintaining instructional efficiency.

Existing commercial tools, such as Turnitin, are effective for general academic writing but are costly and less tailored to the unique characteristics of technical reports. These tools often struggle with the constrained vocabulary of engineering domains, where students may paraphrase content while retaining similar technical concepts. Instructors require objective, quantifiable metrics to assess similarity, enabling fair and consistent evaluation. Moreover, fostering a culture of independent work aligns with the ethical standards expected of engineers, reinforcing the importance of integrity in professional practice.

This paper proposes an automated, open-source tool for measuring text similarity in engineering students' technical reports. The tool employs Term Frequency-Inverse Document Frequency (TF-IDF) vectorization and cosine similarity to generate a similarity matrix, flag documents exceeding a 65% threshold, and produce actionable outputs, including a graphical user interface (GUI) and text reports. By identifying potential plagiarism, the tool supports the educational goal of fostering independent work, aligning with the ethical standards of engineering education. The contributions include a scalable solution tailored to engineering education, an intuitive interface, and an evaluation of its performance on a sample dataset from a geoinformatics course.

The paper is organized as follows: Section II reviews related work, Section III describes the methodology, Section IV presents results and analysis, and Section V concludes with future directions.

II. BACKGROUND AND RELATED WORK

A. Importance of Technical Writing in Engineering Education

Technical reports are integral to engineering curricula, requiring students to document designs, methodologies, and results in a structured format. This process develops critical skills, including analytical thinking, attention to detail, and

effective communication. Independent writing encourages students to synthesize knowledge and innovate, aligning with the professional expectations of engineers. Plagiarism, however, undermines these objectives, necessitating robust detection methods to ensure academic integrity and prepare students for ethical engineering practice. At institutions like Óbuda University, technical writing is emphasized in courses involving geospatial data analysis and modeling, where originality is critical for developing innovative solutions [4].

B. Evolution of Plagiarism Detection

Plagiarism detection has evolved significantly, from manual review to sophisticated computational methods. Early approaches relied on exact text matching, which failed to address paraphrasing or structural similarities in technical documents. The advent of vector-based methods, such as TF-IDF, introduced more robust similarity measures, followed by machine learning and semantic models like Bidirectional Encoder Representations from Transformers (BERT) [3]. In engineering education, the need for domain-specific tools has grown, as standard tools often misinterpret technical terminology as plagiarism due to its repetitive nature [1].

C. Challenges in Plagiarism Detection

Detecting plagiarism in technical reports is challenging due to their structured nature and reliance on domain-specific terminology. For example, geoinformatics reports often describe processes like digital camera calibration, point cloud modeling, or indoor mapping, which inherently share common terms and structures [5]–[7]. Students may produce similar texts due to shared course materials, standardized phrasing, or collaborative learning environments, complicating the distinction between legitimate overlap and plagiarism. Large class sizes, common in engineering programs, further exacerbate the issue, making manual comparison impractical and necessitating automated tools that provide objective similarity metrics [5], [6]. Moreover, the use of AI-supported tools in geoinformatics, such as Visual Lisp programming for geospatial analysis, introduces additional complexity, as students may share code or descriptions, requiring nuanced detection methods [4].

D. Text Similarity Methods

Several methods exist for measuring text similarity:

- **Cosine Similarity with TF-IDF:** Represents documents as vectors based on word frequencies and computes the cosine of the angle between them. It is robust and scalable, making it suitable for technical texts [1]. Its ability to weight terms by their rarity enhances its effectiveness for engineering reports, where domain-specific terms are prevalent.
- **Jaccard Similarity:** Measures word set overlap but ignores word importance, reducing its effectiveness for technical reports with nuanced differences [2].
- **Word Embeddings (e.g., BERT):** Captures semantic relationships, offering superior handling of paraphrasing, but requires significant computational resources and

language-specific models, which may not be readily available for Hungarian technical texts [3].

- **N-gram Analysis:** Detects exact phrase matches but struggles with paraphrasing, limiting its utility in engineering contexts [2].

Recent applications in geoinformatics, such as AI-supported programming for geospatial analysis [4], processing panoramic images into point clouds [5], and indoor mapping with omnidirectional cameras [7], highlight the need for robust similarity measures in technical documentation. These tasks often involve standardized descriptions, making it critical to distinguish between legitimate and plagiarized content in educational settings. Commercial tools like Turnitin combine multiple methods but are costly and less customizable for specific academic needs, particularly in niche fields like geoinformatics.

E. Why Cosine Similarity?

Cosine similarity, paired with TF-IDF, is well-suited for technical reports due to its focus on content relevance over document length. It effectively handles the terminology-heavy nature of engineering texts, such as those in geoinformatics, and is computationally efficient, making it ideal for classroom use. Its ability to accommodate the structured formats and repetitive terminology of technical reports, as seen in tasks like point cloud modeling [5], makes it a practical choice for plagiarism detection in engineering education.

III. METHODOLOGY

This section describes the design and implementation of the proposed similarity detection tool, tailored to engineering students' technical reports.

A. Data Processing

The tool accepts PDF-format technical reports, named in the format `Lastname Firstname_uploadID.pdf`. Text is extracted using the `pdfplumber` library, which converts PDF content into plain text with high accuracy, handling complex layouts common in technical documents. Up to 50 documents are processed to ensure scalability in large classes. Preprocessing includes removing non-text elements (e.g., images, tables) and normalizing text (e.g., converting to lowercase).

B. TF-IDF Vectorization

Each document is converted into a TF-IDF vector, where:

- **Term Frequency (TF)** measures the frequency of a word in a document, normalized by document length.
- **Inverse Document Frequency (IDF)** weights words based on their rarity across the collection, using:

$$\text{IDF}(t) = \log \left(\frac{N}{\text{df}(t)} \right)$$

where N is the number of documents, and $\text{df}(t)$ is the number of documents containing term t .

The `scikit-learn TfidfVectorizer` is used, with stop words (e.g., “and”, “the”) removed and tokenization

customized for Hungarian technical terms (e.g., preserving compound words like “geoinformatikai”). This ensures focus on domain-specific vocabulary, critical for engineering reports.

C. Cosine Similarity

The similarity between two documents A and B is computed as:

$$\text{cosine_similarity}(A, B) = \frac{A \cdot B}{\|A\| \|B\|}$$

The result, scaled to 0–100%, quantifies similarity based on shared terms and their weights. A 65% threshold is used to flag potential plagiarism, adjustable to balance sensitivity and specificity.

D. Implementation

The tool is implemented in Python, using:

- **Libraries:** `pdfplumber` for text extraction, `scikit-learn` for TF-IDF and cosine similarity, `tkinter` for the GUI, and `shutil` for file management.
- **Workflow:**
 - 1) Users select a directory containing PDF reports via the GUI.
 - 2) Text is extracted, tokenized, and converted to TF-IDF vectors.
 - 3) A cosine similarity matrix is computed, with values above 65% highlighted (e.g., `**81.37**`).
 - 4) Flagged documents are copied to a `High` directory, and a `high_similarity.txt` file lists pairwise similarities.
 - 5) The GUI displays the matrix, with diagonal values as `100.00` and lower triangle cells empty for clarity.
- **File Naming:** Names are formatted to display only `Lastname Firstname` by removing `_uploadID.pdf`.
- **Outputs:**
 - A similarity matrix in the GUI, scrollable for large datasets.
 - A `High` directory containing flagged PDFs.
 - A `high_similarity.txt` file, e.g., formatted to fit within a column width using line breaks.

E. Threshold and Output Customization

The 65% threshold was selected as it effectively distinguishes significant content overlap from expected similarities due to shared technical terminology, based on empirical testing on geoinformatics reports [4]. This value can be calibrated by analyzing the distribution of similarity scores in a pilot dataset for a given course size and topic, using statistical methods such as percentile ranking or ROC analysis to optimize sensitivity and specificity. Outputs are customizable, with options to adjust the threshold or export the matrix as a CSV file for further analysis.

TABLE I
SAMPLE SIMILARITY MATRIX FROM A GEOINFORMATICS COURSE DATASET ($N = 50$ REPORTS, ÓBUDA UNIVERSITY).

File	A	B	C	D	E	F
Student A	100.00	81.37	83.98	84.91	80.31	69.20
Student B		100.00	79.41	81.45	73.85	12.45
Student C			100.00	84.40	85.96	76.34
Student D				100.00	81.87	70.77
Student E					100.00	73.77
Student F						100.00

IV. RESULTS AND ANALYSIS

A. Testing

The tool was evaluated on a dataset of 50 technical reports from a geoinformatics course at Óbuda University, focusing on tasks like point cloud modeling and spatial data analysis. Reports were expected to share terminology but required independent descriptions to demonstrate understanding.

B. Case Study

In a specific course module, students submitted reports on 3D panoramic image processing, similar to the tasks described in [5]. The tool processed 50 PDFs, generating a similarity matrix and flagging documents exceeding the 65% threshold. The highest similarities were observed among reports describing similar methodologies, but manual review confirmed plagiarism in several cases where entire sections were copied with minor paraphrasing.

C. Results

The tool produced a similarity matrix, with a subset shown in Table I. Documents exceeding 65% similarity were copied to the `High` directory, and detailed results were saved in `high_similarity.txt`. An example output, formatted to fit within a column, is:

```
Student A: 84.91% similarity with Student D's
           submission,
           83.98% similarity with Student C's
           submission,
           81.37% similarity with Student B's
           submission,
           80.31% similarity with Student E's
           submission,
           69.20% similarity with Student F's
           submission
Student B: 81.45% similarity with Student D's
           submission,
           81.37% similarity with Student A's
           submission,
           79.41% similarity with Student C's
           submission,
           73.85% similarity with Student E's
           submission
```

D. Analysis

The tool successfully identified high-similarity documents, with the 65% threshold effectively flagging potential plagiarism cases. The GUI’s visual representation, with

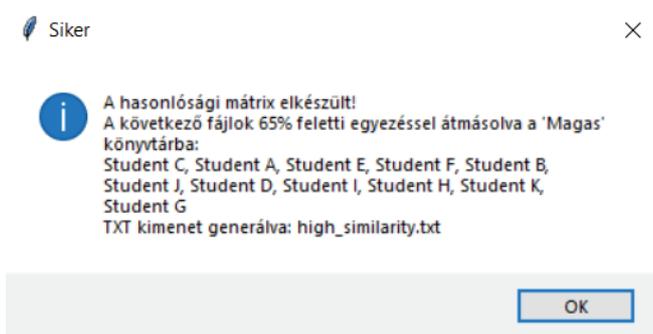


Fig. 1. Results of running the program on a dataset of 50 geoinformatics reports (Óbuda University).

Fájl	Student A	Student B	Student C	Student D	Student E	Student F	Student G	Student H	Student I	Student J	Student K
Student A	100.00	**65.30**	62.84	53.98	**70.14**	**85.47**	**70.17**	**83.36**	48.48	**70.00**	58.82
Student B		100.00	**70.39**	51.26	**78.84**	**73.42**	**73.82**	**86.94**	44.57	**74.01**	**85.73**
Student C			100.00	53.15	**78.14**	**81.50**	**71.43**	**87.20**	46.47	**73.82**	**72.03**
Student D				100.00	60.90	56.11	55.40	55.33	**90.09**	56.91	51.48
Student E					100.00	**82.09**	**79.37**	**72.46**	53.40	**93.31**	**70.31**
Student F						100.00	**74.70**	**88.58**	48.24	**76.40**	**71.33**
Student G							100.00	**82.42**	48.41	**87.22**	**66.03**
Student H								100.00	49.58	**71.94**	64.15
Student I									100.00	49.44	45.48
Student J										100.00	**67.83**
Student K											100.00

Fig. 2. GUI displaying the similarity matrix for 50 student submissions (geoinformatics course, Óbuda University).

highlighted values (e.g., ****81.37****), enabled instructors to quickly identify suspicious submissions (Fig. 2). The `high_similarity.txt` file provided a detailed report, with line breaks ensuring compatibility with the two-column format.

Re-running the tool on the `High` directory resulted in higher similarity scores (e.g., 81.37% increased to 85.96%) due to increased IDF weights in the smaller collection [1]. This highlights the need for consistent threshold calibration across analyses.

E. Educational Impact

By automating similarity detection, the tool streamlines the review process, allowing instructors to focus on pedagogical interventions. It promotes fairness and encourages independent work, aligning with the ethical standards of engineering education. In geoinformatics, where reports often describe complex processes like indoor mapping [7], the tool ensures originality while accommodating domain-specific terminology.

F. Limitations

The tool excels at content-based similarity detection but struggles with semantic paraphrasing (e.g., synonyms like “design” vs. “construction”). Scanned PDFs require OCR, which is not currently supported. Additionally, the GUI uses text-based highlighting (e.g., ****81.37****) due to `tkinter` limitations, which could be improved with graphical enhancements.

V. CONCLUSION AND FUTURE WORK

This paper presented an automated tool for measuring text similarity in engineering students’ technical reports, addressing the challenge of plagiarism detection in higher education. Using TF-IDF vectorization and cosine similarity, the tool provides a scalable, open-source solution that identifies high-similarity documents and supports instructors in fostering independent work. Testing on a geoinformatics dataset demonstrated its effectiveness, with clear outputs and an intuitive interface.

The tool was developed for internal use at Óbuda University to support teaching and assessment; the source code is not publicly available, but all parameters and methods are fully described to ensure reproducibility. Student submissions were anonymized prior to analysis, and data handling complied with institutional ethical guidelines.

Future enhancements include:

- Integrating semantic models (e.g., BERT) to handle paraphrasing [3].
- Adding OCR support for scanned PDFs using libraries like Tesseract.
- Enhancing the GUI with true bold formatting via `tkinter.Canvas`.
- Developing automated threshold optimization based on course-specific terminology.

The tool’s open-source nature encourages further development, contributing to the quality of engineering education, particularly in fields like geoinformatics, by promoting originality and technical proficiency.

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Trends and Challenges in the World of Online Examinations

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Abstract—Online examinations have become an important form of assessment in higher education over the past decade, driven by the digitalization of education and the growing demand for flexible, remotely accessible testing solutions. The COVID-19 pandemic further accelerated this process, as institutions were widely forced to implement digital examination solutions. This shift has raised numerous technical, security, ethical, and psychological issues, necessitating a comprehensive examination. This recognition motivated the present literature review, which aims to highlight the main research directions in online examination studies. Based on the analysis of 1412 studies published in the Scopus database between 2015 and 2025, four main research areas emerge. The first addresses technical solutions and exam organization, with a particular focus on learning management systems and dedicated proctoring platforms. The second deals with security challenges and fraud prevention, where camera monitoring, browser lockdowns, and behavior analysis are emphasized, alongside data privacy concerns. The third research direction examines student experience and perception, highlighting convenience while also addressing increased stress, anxiety, and uncertainty. The fourth area concerns the integration of artificial intelligence, which plays a key role both in proctoring systems and in automated task generation and evaluation, while also raising new ethical dilemmas, particularly with the advent of generative AI. The literature on online examinations identifies three phases: technical experimentation (2015–2019), mass adoption (2020–2021), and critical reassessment (2022–2025). Based on the findings, future challenges include AI-based fraud prevention, addressing data privacy dilemmas, and restoring student trust.

Keywords—online examination, academic integrity, exam security, student experience, artificial intelligence, digital assessment

I. INTRODUCTION

Online examinations have now become one of the key forms of assessment in higher education. The digital transition was first driven by the spread of e-learning and LMS systems, and later made widespread by the COVID-19 pandemic, which forced institutions to shift to online examinations within a short period of time [1, 2, 3]. The digitalization of exams is not merely a technical development but also raises numerous pedagogical and ethical issues. Research highlights that online examinations simultaneously offer flexibility and accessibility, yet challenges related to security, integrity, and student experience remain significant [4, 5, 6].

This study is based on a literature review conducted using the international scientific database Scopus. During the data collection, the period between 2015 and August 30, 2025 was examined, and 1412 relevant publications were identified that address various aspects of online examinations. The following

review was prepared through the systematization and thematic analysis of these studies.

In the literature, several definitions of online examinations can be found; let us consider one of them [7].

„Online examination is an integral part of E-learning solutions for the genuine and fair assessment of students’ performance. The design and execution of online examinations are the most challenging aspects in E-learning. Particularly, online examinations are usually conducted on E-learning platforms without the physical presence of students and instructors at the same place. This creates several loopholes in terms of integrity and security, of online examinations.”

This definition highlights that online examinations represent an independent educational and security system, bringing new challenges from both pedagogical and ethical perspectives [8, 9, 10]. The design and implementation of online examinations are particularly difficult since students and instructors are not in the same physical location, which creates challenges related to security and integrity [7, 11, 12, 13].

II. DEMOGRAPHIC OVERVIEW OF THE LITERATURE

Based on the 1412 studies identified in Scopus between 2015 and 2025 using the search term “online examination” the literature on online examinations can be analyzed according to the following demographic characteristics:

- Annual distribution of the number of studies
- Most frequent keywords
- Distribution by academic disciplines
- Distribution by countries
- Distribution by languages
- Distribution by source types

A. Annual Distribution of Studies

Figure 1 illustrates the number of studies published in the Scopus database on the topic of “online examinations” between 2015 and 2025, with a total of 1412 studies identified.

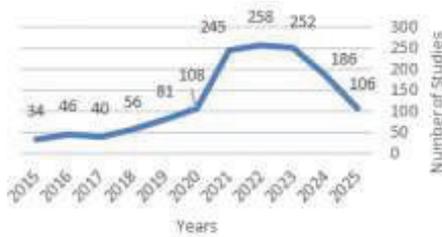


Fig. 1. The evolution in the number of studies published on the topic of “online examinations” between 2015 and 2025.

Based on the data, it can be observed that between 2015 and 2018, the number of publications was relatively low, with 34–56 studies published annually. This period reflects the early research on the topic, when online examinations were not yet widely adopted. Between 2019 and 2022, the number of publications increased significantly, reaching a peak in 2022 (258 studies). This growth was likely due to the expansion of digital education and especially the impact of the COVID-19 pandemic, which led to a sharp rise in interest and research demand for online examinations. Between 2023 and 2025, the numbers show a decreasing trend: 252 studies in 2023, 186 in 2024, and 106 in 2025. This suggests that the major wave of research in the field has concluded, and the number of publications has moderated, although it still remains higher than in the 2015–2018 period. Overall, the figures clearly indicate that the most intensive phase of online examination research occurred during the pandemic (2020–2022), and since then, the number of published studies has gradually normalized.

B. Most Frequent Keywords

Based on the keywords of studies on the topic of “online examinations” in the Scopus database, the following trends can be observed (Figure 2): The most frequent keyword is “Online Exams” (841 occurrences), which is natural since it is the main topic. “E-learning” (483) and “Online Learning” (102) are also common, indicating that research on online examination is closely linked to studies on digital and distance education. “Students” (333) and “Human / People” (127/88) refer to the subjects studied, i.e., students and human factors. “COVID-19” (198) and “Pandemic” (72) highlight the reason for the notable publication surge between 2020 and 2022, when the pandemic accelerated the adoption and study of online examinations. “Teaching” (117), “Education” (89), “Higher Education” (76), “Engineering Education” (82) reflect research focused on different levels and fields of education. “Electronic Assessment” (103), “Examination System” (71), “Academic Integrity” (78), “Cheating” (72) point to the technical and ethical aspects of exam administration. “Face Recognition” (92), “Online Systems” (88), “Machine Learning” (67), “Artificial Intelligence” (67) indicate the use of modern technological tools and solutions in online examinations, for example to prevent cheating or automate exam processes. Overall, the keywords reflect the main directions of the topic: the pandemic-related surge, research on digital education and exam systems, human factors, and the technological and ethical challenges in online examinations.



Fig. 2. Keywords of studies published on the topic of “online examinations”

C. Distribution by Academic Fields

The academic fields of studies on the topic of “online examinations” are distributed as follows (Figure 3): Computer Science (799 studies) is the most dominant field, indicating that research on online examinations primarily focuses on technological solutions, software, systems, and data management. Social Sciences (530) also represent a significant number of studies, reflecting research on human factors, pedagogical methods, student behavior, and ethical issues. Engineering (445) highlights the focus on engineering education and practical examination systems. Decision Sciences (171) and Mathematics (167) refer to the analysis of exam systems, the application of algorithms, assessment methods, and modeling. Pharmacy (156) and Physics and Astronomy (121) indicate research on online examinations in specific scientific fields. Business, Management and Accounting (75), Energy (62), and Psychology (50) are smaller but relevant fields, examining professional and psychological aspects as well as different applications of exam systems. Overall, the distribution of academic fields reflects that online examination research is multidimensional, with technological development, human and pedagogical aspects, and the needs of specific scientific disciplines all playing significant roles.

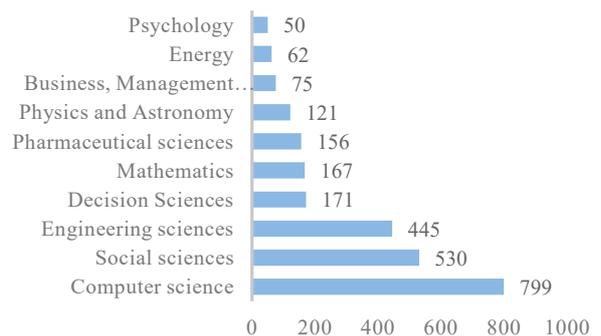


Fig. 3. Disciplinary distribution of studies published on the topic of “online examinations”

D. Distribution by Country

Based on Scopus data, studies on the topic of “online examinations” are distributed by country as follows (Figure 4): India (272 studies) leads the list, indicating that research and implementation of online examinations are particularly active there. This is likely driven by the rapidly growing higher education sector, the expansion of digital education,

and distance learning due to COVID-19. China (179) and the United States (148) also show significant publication activity, reflecting a combination of technological developments, e-learning systems, and the impact of the pandemic. The United Kingdom (73) and Australia (64) represent smaller but active research communities, where digitalization of higher education and online examination research are emphasized. Indonesia (55), Turkey (44), Saudi Arabia (44), Germany (41), and Malaysia (37) are other active countries where online examination systems are studied and implemented, albeit at a smaller scale compared to the top three. Overall, the distribution of publications shows that the topic of online examinations is globally relevant, but the most intensive research has been conducted in Asia (India, China) and North America (USA). The list also includes other countries, highlighting the international impact of the pandemic and digital education.

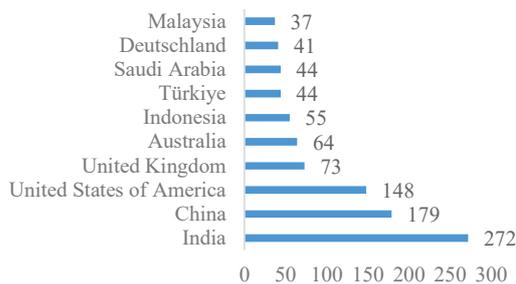


Fig. 4. Geographical distribution of publications on “online examinations” by country

E. Language Distribution

The language distribution of studies on the topic of “online examinations” is as follows: English (1385 studies) dominates, reflecting its role as the main language of international scientific communication and publication. This means that most research is globally accessible, and English-language publications ensure broad scientific visibility. Chinese (10), German (7), Turkish (4), Spanish (4), Persian (2), Russian (1), Italian (1), and Croatian (1) represent significantly smaller shares. This indicates that while research is conducted internationally, the volume of non-English publications is low, and the majority of scientific discourse occurs in English. The language data show that research on online exams is heavily English-centric, with other languages playing only a marginal role, which is a common phenomenon in international scientific publications.

F. Distribution by Source Type

The types of sources for studies on the topic of “online examinations” are distributed as follows (Figure 5): Articles (653 studies) are the most common source type, indicating that research is primarily published in scientific journals. This type of publication reflects high-quality and reliable results due to peer review. Conference papers (614) also represent a significant proportion, suggesting that research on online examinations is actively presented at conferences, where new findings can be shared quickly and technological developments are frequently showcased. Book chapters (63) and books (12) account for a smaller share; these are generally comprehensive, summarizing works that address deeper theoretical aspects of the topic. Conference reviews (33), editorials (23), and notes (5) are supplementary elements of the research discourse, providing critical or summarizing

information, but they do not constitute the majority of publications. The distribution of source types shows that research on online examination is active both in journal and conference publications, while books and review works play a smaller but important complementary role.

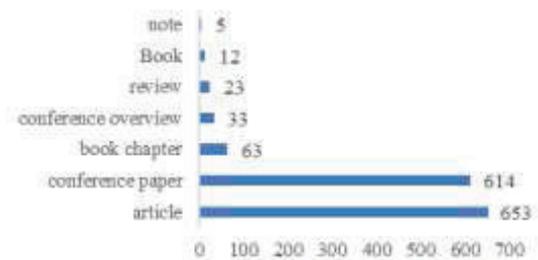


Fig. 5. Evolution of source types in publications related to “online examinations”

III. MAIN RESEARCH DIRECTIONS

Based on 1412 articles in the Scopus database from 2015 to 2025, the literature on online examinations can be divided into four main research directions:

- Technical solutions and exam administration
- Security and cheating prevention
- Student experience and perception
- Artificial intelligence and ethical issues

A. Technical solutions and exam administration

The quality of technological infrastructure is a determining factor. The initial LMS platforms (Moodle) offered advantages such as automated grading and question banks [14, 15, 16]. During the pandemic, institutions often switched to dedicated exam platforms, which provided greater reliability and scalability [17, 18, 19]. Several studies highlight that the main causes of student dissatisfaction are unstable connections and system failures [9, 20, 21]. Other research sees the future in adaptive exam systems, which offer more personalized assessment methods [22]. Technological innovations also include cloud-based examination [23] and the development of exam systems that can run on mobile devices [24, 25].

B. Security and cheating prevention

Cheating prevention is a central research question [26, 27, 28]. Some studies emphasize the advantages of secure browsers and proctoring systems [17, 29, 30]. Proctoring technologies include camera monitoring [31], microphone recording, screen sharing, and biometric identification [32, 33, 34]. Students often respond to these with resistance due to privacy concerns [35]. Other research highlights the use of behavior analysis algorithms, which can detect rule violations based on eye-tracking or background movements [36, 37]. Students themselves often acknowledge that the possibility of cheating is higher during online examinations [27].

C. Student experience and perception

For students, online examinations represent both an advantage and a source of stress [38, 39]. Many appreciate the flexibility and immediate feedback. At the same time, they report that during the sudden transition, students experienced increased stress [38, 39], making their recognition and measurement an important issue as well [40, 41].

Psychological pressure can be reduced through transparent regulations and student-friendly exam design [42]. For Generation Z, the online environment is often more natural, but issues of fairness and transparency remain crucial [43]. Another study found that students feel safer when they can practice with mock exams, which reduces exam anxiety [44].

D. Artificial intelligence and ethical issues

AI-based proctoring systems are capable of automatically detecting suspicious behavior [45, 46, 47, 48]. Automated question generation and adaptive systems supported by artificial intelligence enable more accurate assessment [49, 50]. Some researchers warn that AI systems may have biases and transparency issues [51]. Generative AI, particularly ChatGPT, creates new methods of cheating, prompting educational institutions to reconsider their online examination systems [52, 53]. Additionally, several studies examine AI-assisted automatic grading and feedback [54, 55, 56]. Privacy and ethical dilemmas are among the most important topics of debate [57]. The handling of biometric data requires enhanced regulation [58, 59]. Some researchers advocate for alternative assessment methods that are less invasive [60]. Excessively strict technological control can be counterproductive, as it undermines student trust [61]. Ethical issues include the transparency of AI algorithms and the respect for student rights [62].

IV. CONCLUSION

Over the past decade, online examination has become one of the most significant areas of innovation in education, offering new opportunities as an alternative to traditional assessment methods while also introducing new challenges. Based on the literature, three main developmental phases can be identified: the initial period of experimentation and technological trials (2015–2019), the mass transition forced by the COVID-19 pandemic (2020–2021), and the period of critical reflection and the integration of new technologies, particularly artificial intelligence (2022–2025).

The studies reviewed emphasize that the success of online examinations largely depends on the reliability of the technical infrastructure and the design of a user-friendly exam environment. At the same time, maintaining security and academic integrity remains a central issue, which can be partly addressed through the use of proctoring technologies, biometric identification, and behavior analysis, while also raising privacy and ethical dilemmas.

Research on the student experience shows that while online examinations provide flexibility and accessibility, excessive monitoring, technical failures, and lack of transparency can cause stress and mistrust. Therefore, a key task for the future is to consider student well-being and psychological safety when designing exam systems.

The rise of artificial intelligence represents both a promising development direction and a significant challenge. AI can support automated assessment, adaptive testing, and cheating prevention, while generative models, such as ChatGPT, also introduce new opportunities for cheating that could radically reshape how assessment is approached.

Online examination is not merely a technological innovation but also a complex pedagogical, psychological, and ethical issue. Future research and development could focus on the following key areas:

- the development of transparent and ethical AI-based systems,
- strengthening student trust and satisfaction,
- integrating alternative assessment forms such as open-book exams and project-based tasks,
- tightening data protection and legal regulations,
- examining students' psychological impacts (stress, anxiety, uncertainty) under different assessment methods,
- exploring the relationship between AI tools and students' propensity to cheat,
- investigating instructors' attitudes and experiences across generations and disciplines, and
- developing ethical frameworks to support the responsible integration of AI into online examination practices.

The future of online examination is therefore not only a technological issue but also a social and educational policy matter, which could fundamentally reshape the assessment culture in higher education in the long term.

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Educators' Perceptions of AI and Climate Change in Hungary's Vocational Education

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Abstract— Artificial intelligence (AI) and climate change are two of the most pressing global challenges, significantly influencing vocational education and training (VET). This study explores how teachers in transport and logistics education in Hungary perceive the anticipated impacts of AI and climate change on their professional roles and the broader socio-economic context. The research involved two samples: humanities teachers and vocational instructors from a VET center in Szekesfehervar using an online questionnaire. The survey assessed knowledge, attitudes, perceived risks, and openness to training related to AI and climate change. Results revealed mixed attitudes toward AI: while many teachers were open to its use, a large proportion, especially vocational teachers, viewed it as a security risk. In contrast, climate change elicited more consistent concern, with all vocational teachers agreeing on the need to prepare students for its effects. Generational differences were also observed, with Generation Y teachers showing more optimism toward AI and Generation Z teachers being more critical. The findings highlight the need for practice-oriented training programs that support AI integration and pro-mote sustainability education. With appropriate support, education can play a central role in addressing both technological and ecological challenges.

Keywords— Education, VET Teachers, Artificial Intelligence, Climate Change

I. INTRODUCTION

In the autumn of 2023, we launched the first phase of a broader research initiative aimed at exploring how global megatrends, particularly artificial intelligence (AI) and climate change, are influencing vocational education in Hungary. These two themes have become increasingly prominent in both international and national policy agendas, as they represent some of the most pressing challenges and transformative forces of the 21st century. AI is rapidly reshaping the nature of work, demanding new digital competencies and redefining professional roles across sectors [1]. At the same time, climate change is compelling industries to adopt more sustainable practices, which in turn requires a shift in the knowledge and skills imparted through education and training systems [2].

Our research focused on the transport, logistics, and supply chain sectors, fields that are especially sensitive to both technological innovation and environmental transformation. These industries are not only central to the functioning of the economy but are also undergoing significant change due to automation, digitalization, and the growing emphasis on sustainability [3]. As such, they provide a valuable lens through which to examine how vocational education is responding to these dual pressures.

The first phase of our work involved a systematic review of educational policy documents and curriculum frameworks to assess how AI and climate change are currently addressed in vocational training. This provided a foundational understanding of the institutional and curricular context in which educators operate.

Building on this groundwork, we conducted two rounds of data collection over the past year, engaging vocational teachers to better understand their perceptions of the challenges and opportunities associated with AI and climate change. These surveys captured a wide range of perspectives on how these global trends are expected to impact both professional practice and personal life.

This paper presents a thematic overview of the insights gained from these investigations. A central focus is the comparison of how educators perceive the relative impact of AI and climate change on their work and everyday experiences. By examining these perceptions side by side, we aim to uncover the underlying narratives that shape teachers' attitudes and to identify key trends that may inform the future development of vocational education. The findings offer a timely contribution to ongoing discussions [4] about how education systems can respond to complex, inter-related global challenges in a way that is both forward-looking and grounded in local realities.

II. OVERVIEW OF THE SAMPLES

During the research, data collection was conducted on two separate occasions, involving two distinct samples. In both cases, data were gathered using an online questionnaire. The first sample consisted exclusively of Hungarian language and foreign language teachers. This group is referred to hereafter as the "humanities sample." Data collection for this group took place between April 19 and April 26, 2024, resulting in a total of 67 completed responses.

The second round of data collection occurred between November 23 and November 30, 2024. This sample included instructors from two member institutions of the Szekesfehervar Vocational Training Center. A total of 33 responses were received from this group.

Although both surveys focused primarily on AI, they also included a limited number of questions related to climate change, more so in the vocational sample than in the humanities one. In terms of gender distribution, women were significantly overrepresented in both samples: 91% in the humanities group and 76% in the vocational group. This aligns with broader trends in education, where the profession is increasingly female dominated. These figures are consistent with national data, which show that women make up around

80% of the general teaching workforce and 63% in vocational secondary schools [5].

The average age of respondents was similar in both groups: 49.7 years in the humanities sample and 48 years in the vocational sample. The most common age was 54 in the humanities group and 50 in the vocational group, with median ages of 50 and 49, respectively. These results reflect the aging nature of the teaching profession in Hungary.

Generational analysis revealed that Generation X (born 1965-1980) was the most represented in both samples, while Generation Z (born after 1996) was the least. This is understandable, as many Gen Z individuals are still in education themselves. However, the low representation of Generation Y (born 1981-1996) is concerning, as this group should ideally be in the teaching workforce in greater numbers. The data confirm that the teaching profession is aging, with most respondents aged between 44 and 59, many of whom are approaching retirement.

III. EDUCATORS' EXPERIENCES WITH ARTIFICIAL INTELLIGENCE

In the initial phase of our research, we focused on analyzing educational background documents. Specifically, we examined how the goals of sustainable digital logistics and preparedness for the impacts of climate change are reflected in training pro-grams related to logistics and freight forwarding.

Logistics is a rapidly evolving industry where the effects of AI and digitalization are clearly visible. In the context of the industry 4.0, robotics and automation have become integral to production systems, material handling, storage, transportation, inventory management, and quality control. As a result of digitalization efforts with-in logistics systems, processes supported by information systems, such as intelligent logistics networks and cloud-based technologies, enable the delivery of customized products and services. This transformation demands innovation in skills and competencies. The labor market's evolving expectations, driven by technological advancements, necessitate the continuous updating of training systems and curricula [6].

These principles formed the foundation of the recent comprehensive reform of Hungary's vocational education system, as supported by pre-implementation re-search. Our document-based analysis revealed that although the "Vocational Training 4.0" strategy emphasizes practical, up-to-date, and labor market-relevant knowledge, this vision is only minimally reflected in the official curricula [7].

Subsequent research focused on how the rapid advancement of digitalization and the emergence of AI affect educators' work. The growing presence of AI has sparked societal debate regarding its usefulness and safety. Several researchers have noted that educators are concerned about workplace changes, the spread of misinformation, and threats to personal privacy [8]. The COVID-19 pandemic exposed significant gaps in digital competencies but also triggered a wave of innovation. De-spite the challenges, the pressure to adapt to new expectations led to AI being seen as a catalyst for progress, offering new opportunities in education [9]. While AI-based applications are often seen as helpful and convenient, they also raise ethical dilemmas and data security concerns [10]. The traditional role of the teacher as the sole source of knowledge is being redefined, as AI reshapes human

relationships and may diminish the authority of educators [11].

Looking ahead, and considering labor market expectations [12], the application of AI in education is important from three perspectives:

- Goal: understanding and teaching AI itself,
- Tool: using AI to provide effective support,
- Impact: leveraging AI's innovative potential to enhance both teaching and learning.

Based on these considerations, we conducted surveys among educators in both humanities and vocational fields. We asked humanities teachers about their aware-ness of and openness to AI-based applications. Among vocational educators, we extended the inquiry to include perceptions of safety and vulnerability.

Among humanities educators, 25% reported no familiarity with AI applications, while more than half actively use them. On a scale from 1 to 10, their average self-reported knowledge level was 4. Across generations, there were no significant differences in awareness or openness. Slightly more than 50% of teachers from all generations expressed willingness to use AI-based tools. In total, 32 different applications were mentioned.

In the vocational sample, educators rated their awareness and openness to digital and AI technologies at an average of 5.2 (on a 1–10 scale).

- 67% reported using AI-based applications.
- When asked about AI's impact on their subject matter and language use, humanities teachers gave average ratings between 2.6 and 3 (on a 1–5 scale), with Generation Y reporting the strongest perceived impact.

In the humanities sample, open-ended responses highlighted both positive and negative effects of AI, especially regarding students and their learning. Teachers were divided on creativity, some saw AI as enhancing it, others as diminishing it. Positive aspects included increased efficiency, support, engagement, motivation, and a sense of achievement. However, negative effects were noted in areas such as skill development, independence, and concentration. Interestingly, no respondents mentioned security concerns.

Among vocational educators, we focused on awareness, openness, and perceptions of risk and safety. As mentioned, their average awareness score was 5.2, while open-ness to digital thinking and transition scored higher at 6.5.

Concerns about AI-related risks and distrust are prevalent in society and among educators. Our findings confirmed this:

- 85% of vocational educators viewed AI as a security risk,
- 6% did not,
- 9% were unsure.

Generational analysis revealed that Generation Y viewed AI positively as a new opportunity, while no members of Generation Z expressed a positive view. Despite these concerns, when asked who AI poses the greatest threat to, 30% of vocational educators said it posed no threat to anyone.

However, 43% believed it was most dangerous for younger generations (see Fig. 1).

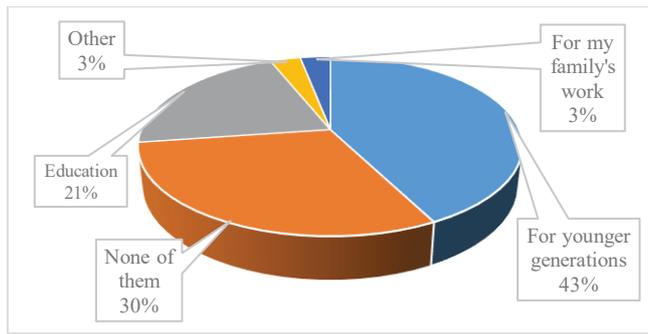


Fig.1. Assessing artificial intelligence vulnerability (professional education)

Both studies also assessed educators' willingness to participate in AI-related training

- Among humanities educators, 80% were open to training, while 15% were uncertain.
- Rejection of training was mostly limited to a few members of the Baby Boomer and Generation X.
- Language teachers were the most willing to participate.
- The vocational sample showed similar results:
- 88% were open to training,
- The remaining 12%, primarily Baby Boomers and Generation X, declined the opportunity.

Our research revealed that while educators approach AI with caution, their awareness is moderate, and they are generally open to development. They recognize the risks but are willing to engage with the opportunities AI presents.

IV. EDUCATORS' EXPERIENCES WITH CLIMATE CHANGE

The effects of climate change, especially recent weather anomalies, provide ample justification for integrating this topic into education. A striking example is Hungary's October 2024 average temperature, which exceeded the long-term average by 0.7°C, continuing a 17-month trend of above-average national temperatures [13].

Beyond temperature, climate change has broader implications. Dr. László Teknős highlights how climate change contributes to civilization-level conflicts and outlines the expanding responsibilities of disaster management authorities, supported by extensive data [14].

Climate change also affects the financial sector. In 2021, the Hungarian National Bank (MNB) [15] published a report emphasizing the integration of green considerations into monetary policy. The MNB demonstrated how climate-related risks influence the fulfillment of its core responsibilities.

Clearly, climate change impacts many aspects of life. In education, it is no longer sufficient to simply raise awareness about environmental protection and sustainability. Students must be prepared for the real-world consequences of climate change.

To support this preparation, it is essential to understand educators' perspectives and attitudes on the topic. In both of

our samples, we asked respondents whether they believed climate change or AI would bring greater changes to their personal lives in the next 5-10 years (see Fig. 2, Fig. 3).

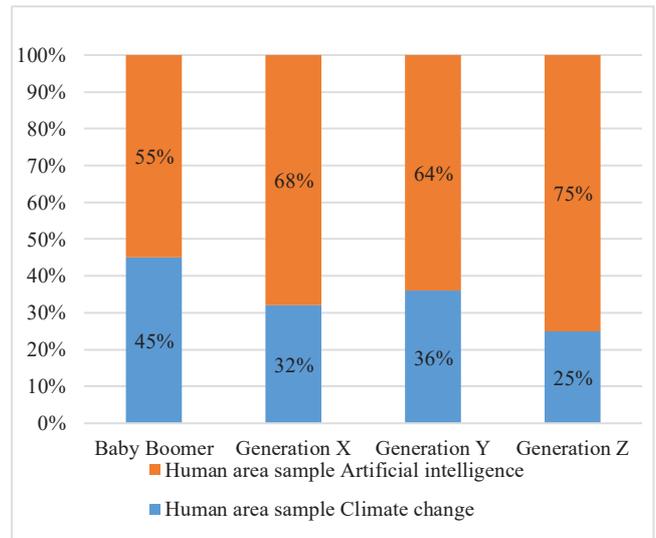


Fig. 2. Climate change or artificial intelligence will make a bigger difference in teachers' life in the next 5-10 years.

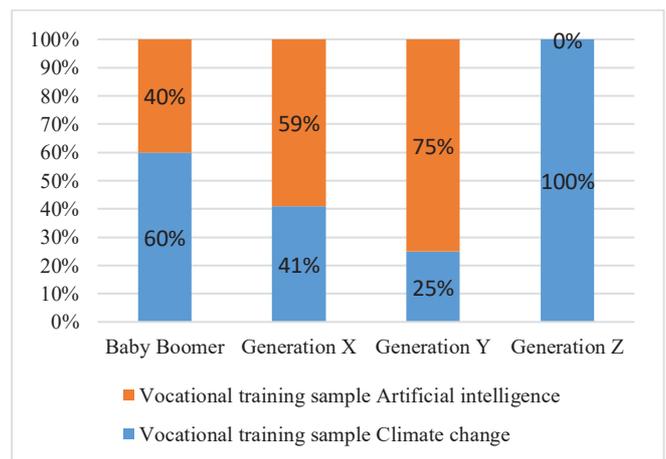


Fig 3. Climate change or artificial intelligence will make a bigger difference in teachers' life in the next 5-10 years.

It became clear from our analysis that in the humanities sample, artificial intelligence (AI) was consistently perceived as the more influential factor. Educators working in this field viewed AI as having a greater impact on their personal lives than climate change, across all generations. In contrast, the vocational training sample presented a more nuanced and mixed picture.

One particularly interesting finding relates to the differing responses of Generation Z across the two samples. In the humanities sample, 75% of Gen Z respondents considered AI to be a stronger influence on their personal lives than climate change. However, in the vocational training sample, 100% of Gen Z respondents identified climate change as the more significant factor.

We also asked participants: "Which do you believe will have a greater impact on the economy and society over the next 5-10 years: climate change or the spread of artificial intelligence?"

The responses to this question were remarkably consistent across both samples. All generations agreed that AI would have a stronger influence on shaping the socio-economic system soon (see Fig 4., Fig. 5).

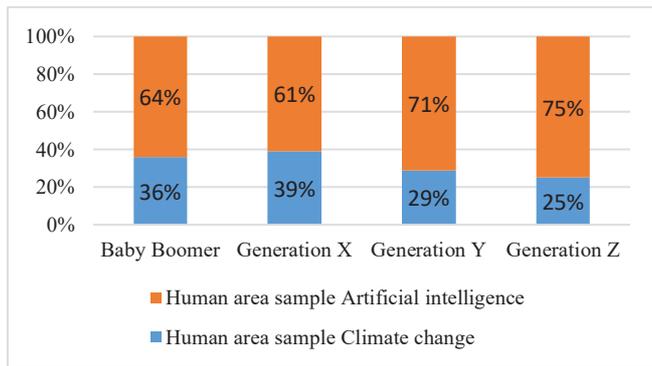


Fig 4. The perspectives of educators in the humanities regarding which factor, climate change or the spread of artificial intelligence, will have a greater impact on the economy-society system over the next 5 to 10 years.

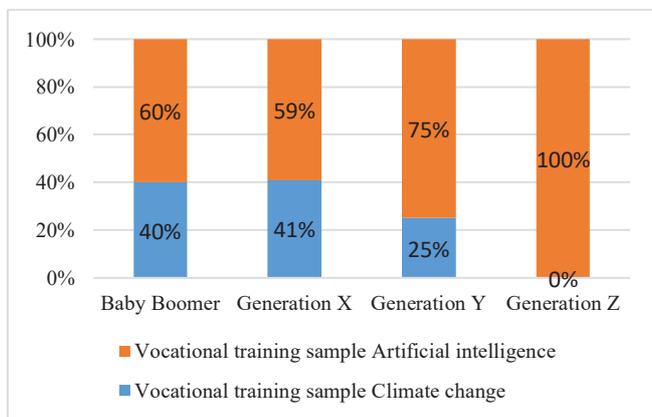


Fig 5. The perspectives of vocational trainers regarding which factor, climate change or the spread of artificial intelligence, will have a greater impact on the economy-society system over the next 5 to 10 years.

When analyzing both questions together, two key observations emerged:

1. Personal vs. Societal Impact Perception

In four instances, respondents rated climate change as having a greater impact on their personal lives than AI. However, when asked about the broader societal and economic impact, AI was consistently rated higher. These discrepancies were highlighted in Table 2 of the original study, with red shading indicating where climate change was rated higher for personal impact, and green where the values were equal.

This raises an intriguing question: Why do individuals perceive climate change as more impactful in their own lives, yet see AI as the dominant force at the societal level?

2. Generation Z's Divergent Views

Although the number of Gen Z respondents was low in both samples (a limitation to consider), their responses were notably different between the two groups.

- In the humanities sample, Gen Z respondents consistently rated AI as the more influential factor for both personal and societal impact.

- In the vocational training sample, Gen Z respondents saw climate change as the stronger influence on their personal lives, but AI as the more significant force shaping society and the economy.

This contrast prompts further reflection: Why do Gen Z educators perceive climate change as a stronger personal influence, yet not as a dominant societal force?

Although this aspect of the study was investigated exclusively within the vocational training sample, it yielded valuable insights into educators' attitudes toward climate change education. Participants were asked two key questions to assess their perspectives:

First, they were asked whether students should be prepared within the education system for the anticipated consequences of climate change. In response, all participants (100%) affirmed the importance of such preparation, indicating a unanimous consensus on the necessity of integrating climate-related content into educational curricula.

Second, respondents were asked whether they would be willing to voluntarily teach a subject focused on the phenomena and expected consequences of climate change, assuming no formal qualification requirements were imposed. In this case, 57% of the educators expressed a willingness to undertake such a role. These findings suggest a strong recognition among vocational educators of the importance of climate change education, with a majority indicating not only awareness but also a readiness to contribute actively to students' preparedness for future environmental challenges.

V. CONCLUSION

In summarizing our research, it is important to emphasize that our surveys are not representative due to the small sample size. Therefore, the findings offer only a limited insight into educators' attitudes and forward-looking perspectives regarding artificial intelligence (AI) and climate change. This limitation affects the generalizability of the results.

Even with this in mind, it is evident that both topics are of significant interest to the teaching community. Regarding AI, educators tend to approach the topic critically and with caution. However, they do not view it solely as a threat, they also recognize its potential and opportunities.

Overall, the data suggest that educators are open to training and development in both areas. The COVID-19 pandemic forced society into a rapid digital transition, which, despite its challenges, led to clear innovation. The role of the educator has undergone a substantial transformation in recent years, a shift accelerated by the rise of AI and digitalization. The open-mindedness demonstrated by educators in our study can serve as a model. The use of AI applications may support the education of new generations and better prepare students for the labor market. Our findings also show that AI-based tools offer numerous advantages: they can bridge generational gaps and enhance both teaching and learning.

Collaborative brainstorming among educators could help share positive experiences, demonstrate practical applications, and provide valuable support, especially for older generations of teachers.

In terms of climate change, educators clearly recognize the importance of addressing the topic and passing on related knowledge. However, when asked to weigh the impacts of AI and climate change on the economy and society, all generations identified AI as the more transformative force. This may be due to the more visible and immediate nature of AI's advancement, whereas the effects of climate change, though serious, are often perceived as slower or less tangible.

To raise awareness of climate change, the focus should not be on persuasion or fear, but rather on encouraging small, forward-looking steps. By integrating environmental awareness into education and preparing students for future challenges, the teaching profession can play a key role in mitigating the effects of climate change across all areas of education.

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Civil protection training and international experiences in the context of climate change

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Abstract— In today's rapidly changing world, protecting the lives and values of the civilian population is a task of paramount importance. Society is threatened by an increasing number of hazards, including natural disasters, epidemics, armed conflicts, and technological crises. In recent years, we have all experienced the effects of the global pandemic and the consequences of the war in a neighboring country, which have highlighted the importance of preparedness. Civil protection can play a key role in preparing the population, particularly through education and training. Raising public awareness, recognizing emergencies, and learning how to respond appropriately are essential to mitigating the effects of disasters. In the following, we will focus primarily on the risks posed by climate change and examine the training opportunities available in the field of civil protection. In addition, we will use international examples to illustrate the experiences of other countries in preparing the population and managing risks.

Keywords— Civil protection; climate change; education

I. INTRODUCTION

The aim of the study is to explore how climate change affects civil protection education tasks and opportunities. The study also aims to identify international best practices that can be applied in Hungary or that can complement the opportunities already available in our country. Following a review of European literature, the study is based on an analysis of the documents uncovered.

The world around us is constantly changing and transforming. This transformation affects almost every area of our lives. Our economy, society, and the expectations of generations within it are constantly changing [1], but our environment is also undergoing transformation.

In many cases, these transformations and changes paint a positive picture. Think of advances in science, transportation, and the emergence of new drives alongside safety and cognitive transportation [2]. Of course, the list could go on and on.

Unfortunately, however, there is another side to the coin, where the changes also have negative consequences. There are numerous facts that could be presented here. One particularly shocking negative fact can be found in the WWF's Living Planet Report, which shows a 73% decline in the average size of observed wildlife populations in just 50 years [3]. This ecological change certainly has and will continue to have an impact on our lives. Ecological change is not only evident in the decline or extinction of species, but also in the fact that changes and transformations in habitats can lead to new

threats in certain areas. One example of this is the new species of tick that has been found in Hungary [4].

People and society must adapt to changes in the environment and circumstances surrounding us. Adaptation is also necessary because a significant proportion of these transformations pose a threat to society and to individual members of society alike. These threats can seriously endanger not only human life, but also economic assets. Furthermore, they can pose a threat to the stability of society.

Threats can basically be divided into civilizational, human, and environmental threats [5]. Human threats include events such as terrorism, wars, and disinformation campaigns. Civilizational threats include industrial disasters and critical infrastructure exposure. Natural hazards include earthquakes and extreme weather events.

Hungary can be considered a safe place in terms of man-made emergencies. Our country ranks high in two data sets published on the Vision of Humanity website. The Global Peace Index gives Hungary a score of 1.5 in 2025, making it the 17th most peaceful country in the world. Similarly, Hungary scored 0 on the Global Terrorism Index based on data from 2024. For both indicators, the lower the score, the safer the country is [6]. Of course, this does not mean that Hungary does not have to deal with these threats.

In the following, we will focus our attention on natural hazards due to the above reasons. Considering that natural hazards can cause serious material damage and, unfortunately, also claim human lives.

The European Environment Agency published statistical data on economic and human losses in 2024. According to the data, between 1980 and 2023, the 27 member states of the European Union suffered economic losses of €738,280 million due to extreme weather and climate events. This amounts to an average of more than €17,169 million per year. This is a significant figure, but when we add the number of human casualties, which is 241,587 [7], even developed countries have to reckon with these dangers.

II. CHANGES IN THE WEATHER IN HUNGARY

Since measurements began in 1901, numerous changes and transformations have been observed in Hungary's weather. These changes are examined by meteorology using several indicators and measurements. In the following, we will briefly focus on just two areas (temperature changes and changes in precipitation) to illustrate these changes.

A. Changes observed in Hungary's temperature data

In Hungary, temperature data series show several data points and trends. From this vast amount of data, we focus primarily on high and low temperature data.

Signs of warming are particularly evident when examining heat indices [8]. Over the past 123 years, the number of hot days, when the daily maximum temperature reaches or exceeds 30 °C, has increased by more than 15 days per year. Hot days, when the maximum temperature reaches or exceeds 35 °C, have also become more frequent, increasing by more than 2.5 days. In addition, tropical nights, when the daily minimum temperature does not fall below 20 °C, have become more frequent by more than 2.4 days.

At the same time, cold indices [9] show a downward trend. The number of frost days, when the daily minimum temperature is 0 °C or lower, has decreased by more than 20 days. The number of harsh days, when the minimum temperature is -10 °C or lower, has decreased by more than 8 days. The number of winter days, when the daily maximum temperature does not exceed 0 °C, has decreased by more than 9 days.

The above data clearly shows the direction of climate change: the number of warmer days is increasing, while the number of colder days is decreasing. This trend is evident not only in statistical data, but also in everyday experience.

B. Trends visible in precipitation distribution in Hungary

To illustrate domestic precipitation conditions, we used weather data for Hungary published by the Central Statistical Office [10]. During the study, we examined the number of rainy days and the amount of precipitation measured in millimeters. Rainy days are defined as days when the amount of precipitation was at least 0.1 millimeters.

During the investigation, the data from the database was plotted on a graph, followed by the addition of a linear trend line. The trend line helps to determine the nature of the changes in the data. After examining the data, we can make the following observations.

- A slight decrease in the amount of precipitation over the course of a year can be seen based on the trend line.
- There has also been a decrease in the number of rainy days. In other words, we can expect fewer and fewer rainy days over time. This decrease is even more apparent when we examine the 10-year moving average of the number of rainy days. Since measurements began, the 10-year moving average of rainy days has fallen from around 170 days per year to less than 140 days per year.
- However, the amount of precipitation falling on a single rainy day has increased. Based on the data, it can be concluded that the amount of precipitation per rainy day has increased by more than 0.5 millimeters.

This is also supported by an examination of the occurrence of heavy rainfall over a single day. According to data from Hungaro Met Zrt, the number of days when precipitation exceeds 20 mm, 30 mm, or even 40 mm per day has increased over the past 120 years [11].

C. Hazards arising from the expected weather conditions in our country

Trends are emerging from meteorological measurements taken in our country over more than 100 years. Warming is becoming increasingly prominent in our weather, while colder periods are gradually decreasing.

Furthermore, the amount of precipitation is decreasing minimally, but the amount falling in each period is increasing.

The following dangers can be deduced from the two changes mentioned above. On the one hand, warming weather and decreasing precipitation increase the risk of drought. This is compounded by the fact that the disappearance of frost periods in winter increases soil drying. On the other hand, dry soil and large amounts of precipitation falling at once increase the risk of floods and flash floods.

These risks, along with other much broader risks, are included in Hungary's disaster risk assessment report [12] among the risks associated with extreme weather and water. In addition to the risks of drought and flash floods, these include, among others:

- Severe storms
- Extreme temperatures
- Forest fires
- Hailstorms
- Flooding
- Inland flooding.

We must adapt to these changing weather conditions and prepare to mitigate the damage. As Schweickhardt Gotthilf writes: "*Climate change is transforming the weather in our country, and with it, our defenses against natural disasters*" [13].

III. DISASTER MANAGEMENT AND CIVIL PROTECTION

From the above, it is easy to understand that it is necessary to establish a defense system and develop the existing system in our country as well. Currently, the disaster management system provides the space and opportunity for these activities in our country.

At present, these activities are regulated by Act CXXXVIII of 2011 on disaster management and the amendment of certain related acts.

Under the above-mentioned legislation and supplementary regulations, three major areas can be distinguished within the field of disaster management:

1. fire protection,
2. civil protection,
3. industrial safety [13].

Two of these three areas, fire protection and civil protection, have a long history, as there are written records of fire protection dating back to the reign of Stephen I. Organized fire departments began operating in Hungary in the 1870s.

The first steps in civil protection can also be traced back to the last century, when this protective activity began with the organization of air defense [14].

According to Section 3(20) of the legislation:

"Civil protection: a system of tasks, tools, and measures for society as a whole, the purpose of which is to protect the lives of the population in the event of a disaster or armed conflict, to ensure the conditions for survival, and to prepare

the population to overcome the effects of such events and create the conditions for survival." [15]

From the above definition, we can see that civil protection activities are very diverse and cover a wide range of tasks. Without claiming to be exhaustive, civil protection must perform the following tasks in relation to climate change:

- preparing the population for the rules of conduct necessary during defense,
- providing information, warnings, and alerts,
- maintaining protective structures,
- participating in the evacuation of the population, organizing relocation and reception if necessary,
- ensuring the protection of goods necessary for subsistence (water, food, feed, medicines, etc.),
- providing first aid,
- disinfection.

In addition to the above, civil protection also performs several activities that support defense and the maintenance of public services [13].

Civil protection may involve individuals in these tasks on a voluntary or compulsory basis. The individuals involved may perform various types of tasks, which can typically be divided into the areas of information and communication, civil protection, logistics, health, and technical and damage assessment activities.

IV. CIVIL PROTECTION AND EDUCATION

The previous chapter showed that climate change makes it necessary to prepare and inform people, as our weather and climate are changing. As a result, our country must reckon with risks that are becoming increasingly severe and, in some cases, more frequent.

We can also see that civil protection, operating within the disaster management system, can provide the appropriate organizational background and knowledge.

If this can be achieved, a more resilient society that recognizes dangers and responds to them appropriately can be developed. In the following, we will review some international examples that may be useful and worthy of consideration in our country, without claiming to be exhaustive.

Manuel Ribeiro, Paulo Gil Martins, and Ana Paula Oliveira provide a comprehensive analysis of the engineering approach to civil protection in a world struggling with digitalization and the phenomenon of volatility, uncertainty, complexity, and ambiguity (VUCA) [16]. According to their approach, the education of civil protection engineers should be based on three important pillars, namely:

- Scientific research on hazards and risks,
- Practical training,
- Development of civic competencies and active social participation.

These can be used to increase society's resilience, as well as the culture of safety and its acceptance. It thus plays a key role in creating a safer and more resilient society.

In their paper, they emphasize the importance of information and communication technology and the fact that technological progress simultaneously increases security and creates new risks.

A subsequent paper examining the adult and continuing education system for civil protection in Germany [17] comes to some interesting conclusions based on a systematic review of the literature.

Among other things, the current civil protection training and its decentralized status can be traced back to the period following World War II. According to the study, both civil protection and adult education are decentralized in Germany. As a result, many institutions and numerous actors are involved. They emphasize that adult education plays an important role in the training of both the public and professional staff. Furthermore, adult education can help increase the resilience of the population, especially in the era of climate change and hybrid warfare.

A study on the Czech Republic presents a completely different approach to civil protection than previous studies. Tomáš Milěj and Peter Marinič [5] show that disaster risk reduction has been included in primary and secondary school curricula in the Czech Republic since 2010. The education of Czech students in this area plays an important role in building the population's resilience to various types of disasters.

In addition to highlighting the importance of disaster management training in the education system, the authors also mention that local governments hold training courses. Furthermore, the authors feel it is important to emphasize that training the population is not enough. To provide adequate theoretical and practical training, it is also necessary to provide appropriate training to students in teacher training colleges. They will be the ones who pass on and convey this knowledge to students.

The study emphasizes that education is essential if we want to build and develop the population's resilience to disasters.

V. CONCLUSION

Based on the findings presented in the introductory section of this study, it can be concluded that Hungary must consider the risks and dangers arising from climate change, as well as the potential disasters that may result from them. Of course, this does not mean that other risks, such as terrorism and industrial disasters, should be ignored. However, climate change is likely to increase the occurrence and potential of natural disasters.

We have also seen that the domestic legal and organizational environment provides disaster management, and within that, civil protection, with sufficient scope and opportunity to equip members of society with the knowledge to deal with such disasters.

We then saw some practical examples of how this preparation and knowledge transfer is manifested at the international level.

A. Experiences and recommendations for the development of the domestic education system

It is probably important to train professional civil protection engineers who have special multidisciplinary knowledge, as we can see in the article by Manuel Ribeiro,

Paulo Gil Martins, and Ana Paula Oliveira [16]. In Hungary, the disaster management training program at the National University of Public Service does not have this name, but it takes a similar approach. This training is available at both the bachelor's and master's levels. Within the bachelor's program, the disaster management operations specialization provides detailed knowledge related to civil protection.

Lacher and Rohs describe a practice in Germany [17] that offers opportunities for teaching disaster management and civil protection skills in adult education. Such skills can also be acquired in Hungary. In the new training structure, relevant training courses can be found among the professional qualifications that can be obtained through vocational training organized by vocational training institutions or adult education centers. These include the Disaster Management Assistant qualification and the Disaster Management Administrator qualification, which builds on this training. Although these courses are only classified as secondary education, they are still an effective way of imparting a broader range of knowledge on the subject.

The example presented and described among the international examples reported that the Czech education system already includes disaster management and civil protection training in primary and secondary schools [5]. In Hungary, the National Core Curriculum [18] includes the concept of disaster management as a key concept within the subject of civics. However, it is clear from the structure of the subject that this is not its main content. It can therefore be clearly recommended that the next revision of the National Core Curriculum should place greater emphasis on teaching disaster management and civil protection.

The Czech example [5] also states that to increase society's resilience to disasters, this area must be clearly reflected in teacher education and training. I have not found any relevant information on the transfer of such knowledge in the field of teacher training in Hungary.

Based on the above, it can be recommended that Hungarian higher education institutions providing teacher training broaden the knowledge they impart to include such topics. One possible solution would be for institutions involved in disaster management training to advertise continuing education courses for educators, instructors, and teachers specifically related to disaster management and civil protection. The importance and significance of this is stated in an article by László Bérczi and Krisztina Kállai, according to which one of the tools for creating a resilient society is, among other things, the establishment of a stable education system [19].

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When examining students' time management habits, it is particularly important to explore whether they employ time planning consistently and what concrete strategies they apply in their daily routines. Addressing these questions can support the design of more targeted learning methodology interventions, especially in higher education, where student autonomy and responsibility are significantly heightened [5].

Research has shown that time planning not only improves academic performance but also has a positive impact on self-regulation, concentration, and learning motivation [6]. Consequently, it is of special importance to investigate how students integrate time management techniques into their everyday lives.

B. Motivation in Learning

Motivation is one of the most significant driving forces of the learning process. In higher education, it is particularly important that students are motivated not only by external expectations but also by intrinsic factors [7]. Intrinsic motivation stems from the joy of learning and genuine interest. This type of motivation results in deeper and more sustainable knowledge acquisition. For part-time students, a career change often represents a turning point in their professional trajectories. In such cases, existential changes, professional burnout, organizational restructuring, or the technological obsolescence of job roles may prompt individuals to pursue further higher education [8]. Thus, career change or the acquisition of a new profession may become not only an opportunity but a necessity. With digital transformation, artificial intelligence, and automation reshaping labor markets, many traditional jobs are disappearing, evolving, or requiring entirely new skills [9].

Extrinsic motivation, on the other hand, refers to external incentives such as grades, scholarships, recognition, or the promise of future career opportunities. While extrinsic motivation may effectively boost short-term performance, it proves sustainable in the long term only if it fosters the development and strengthening of intrinsic motivation [10].

Grades, for example, often act as external motivators, with students perceiving high marks as rewards that provide feedback on their performance and influence their self-esteem. Scholarships serve as both financial and prestige-based incentives, strengthening academic commitment—especially for students facing financial barriers to higher education [11]. Teacher or institutional recognition—such as praise, awards, or public acknowledgement—enhances students' self-confidence and reinforces positive learning behaviors, thereby exerting a motivating effect [12]. Finally, the prospect of future career opportunities—such as a desirable job or professional advancement—functions as an external goal that motivates students to pursue their studies consciously and purposefully [13].

C. Awareness in Learning

Conscious learning constitutes a key competence in higher education, encompassing students' ability to reflect on their own learning processes, set goals, and independently regulate their learning strategies [14]. This metacognitive awareness enables learners to recognize both their strengths and areas for improvement and to adjust their learning behaviors accordingly [15].

Self-regulated learning (SRL) is a cyclical process in which students set goals, plan their learning activities, apply

appropriate cognitive and metacognitive strategies, and subsequently evaluate their performance [16]. This process is particularly relevant in higher education, where autonomy and responsibility are significantly increased [17]. Developing metacognitive skills not only improves academic outcomes but also contributes to enhanced self-confidence, problem-solving abilities, and lifelong learning competences [18].

D. Applied Learning Techniques

Learning style refers to an individual's preferred mode of processing information, which determines how they most effectively acquire new knowledge. One of the most widely known and applied models is the VARK (Visual, Auditory, Reading/Writing, Kinesthetic), developed by Neil Fleming in the late 1980s. This model distinguishes four sensory modalities that reflect individual learning preferences [19]. Importantly, these learning styles are not mutually exclusive, as many students employ multiple modalities to maximize learning effectiveness. The primary aim of the VARK model is to help learners recognize their learning preferences and tailor their strategies accordingly [19].

Visual learners process information most effectively through graphical elements such as diagrams, charts, maps, and symbols. They benefit from visual representations that facilitate comprehension, recognition of relationships, and structured thinking. For these students, material presented visually often leads to improved understanding and recall.

Auditory learners acquire knowledge most effectively through listening, such as during lectures, discussions, or auditory materials. They process information through verbal explanations and interpersonal communication, often recalling spoken information with ease. Group discussions, oral recitation, and audio-based learning activities are particularly beneficial for them.

Reading/Writing learners prefer textual information and rely heavily on note-taking, reading, writing summaries, and creating lists. They tend to thrive in traditional academic environments where written texts dominate, and they benefit from organizing knowledge through writing and textual synthesis.

Kinesthetic learners learn best through physical activity, experimentation, and hands-on practice. Activities such as experiments, modeling, role-playing, fieldwork, and interactive exercises are most effective for them. These learners require active engagement and direct interaction with the material to fully internalize knowledge.

III. PROCESSING OF THE QUESTIONNAIRE

The primary objective of the quantitative research was to validate the relevance and necessity of learning methodology in contemporary higher education. The participants of the study were first- and second-year full-time students enrolled at the Alba Regia Faculty of Óbuda University. In total, 78 students completed the questionnaire via their mobile phones using the Google Forms application.

From the first-year cohort, 25 students were enrolled in Business and Management, 16 in Mechanical Engineering, 14 in Electrical Engineering, and 10 in Technical Management. Among the second-year students, only those from the Business and Management program participated, with a total of 13 respondents.

The questionnaire primarily focused on how the introduction of structured learning instruction influenced students' motivation to learn, the development of their time-management skills, and their capacity for conscious learning. The responses provided a realistic picture of students' learning methods, learning habits, and their adaptation to university life. Another central aim of the study was to assess whether the learning attitudes of first-year students could be influenced. The findings are expected to support educators in refining their pedagogical approaches, potentially adopting entirely new methods tailored to contemporary students, thereby assisting them in successfully becoming professional engineers.

The research was conducted in May 2025. Students had commenced their studies in the 2024/2025 academic year under the new "F" curriculum, which had been introduced in the preceding academic year. Data collection concentrated on full-time students, and the qualitative evaluation was developed based on the most relevant and frequently occurring responses.

The first section of the questionnaire focused primarily on time management strategies, as time allocation plays a pivotal role in the learning process. Effective scheduling and adherence to a well-structured timetable can significantly enhance learning efficiency. Figure 2 illustrates how students assessed their own time management strategies and the extent to which they considered them effective.

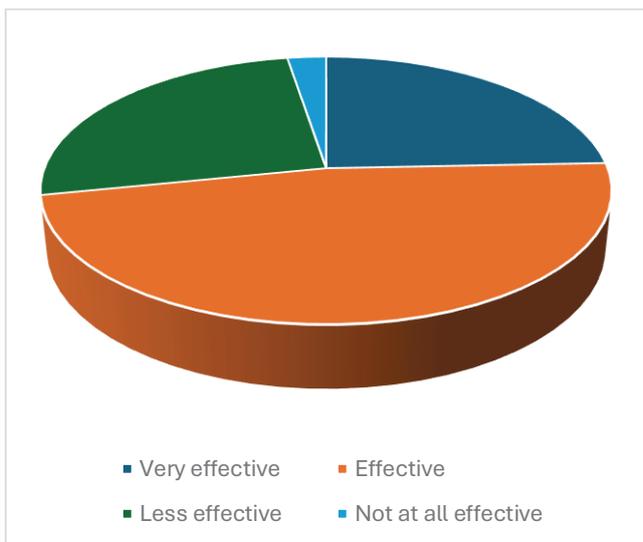


Fig.2. How effective do you feel your time management strategies are?

An additional key question concerned whether students employ time planning in their daily lives. The majority of respondents indicated that they make use of the calendar function on their mobile phones or record their daily tasks in a notebook, while some also rely on weekly and monthly planners. Only 9% of the respondents—equivalent to 7 students—reported that they do not use any form of time planner at all. Although this proportion cannot be considered unfavorable, there remains potential for improvement in order to make students' time management more structured and focused, as shown in Figure 3.

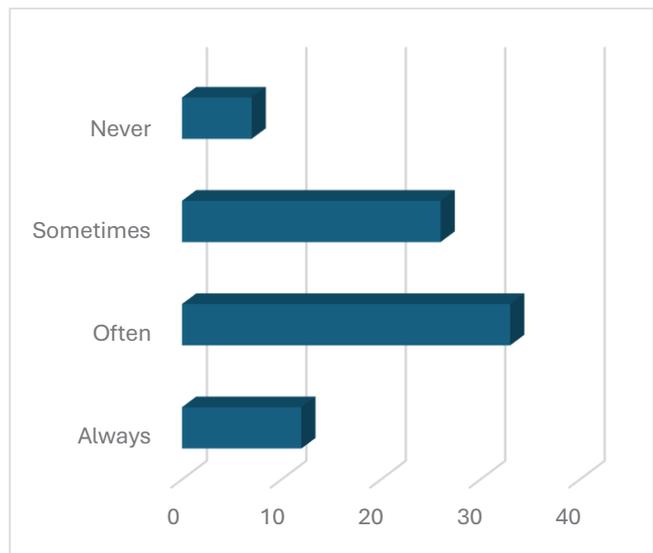


Fig.3. Do you use time planning regularly?

The next question in the study addressed how students implement time planning and what types of planners they use. Surprisingly, the use of digital planners was relatively low, with only 38.5% of respondents indicating that they rely on such tools. In the upcoming academic year, greater emphasis should be placed on this aspect within the section of learning methodology that highlights the importance of time management. As shown in Figure 4 for today's students, paying closer attention to the conscious allocation of time would be particularly beneficial.

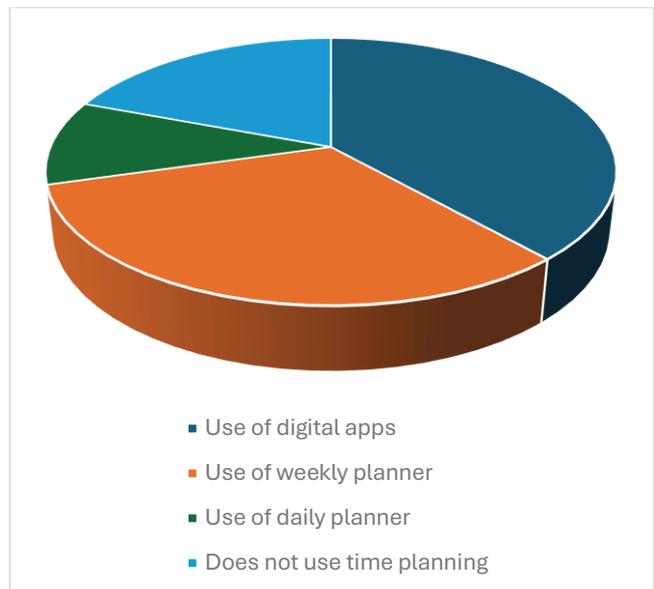


Fig.4. How do you implement time planning in your everyday life?

As expected, the responses to the question regarding students' perceived level of motivation in learning followed a predictable pattern. Assuming that the majority had chosen their field of study and higher education institution in line with their personal interests, it is unsurprising that most students reported being motivated to learn. Nevertheless, 12.8% of respondents indicated that they were either not motivated or only minimally motivated, as shown in Figure 5.

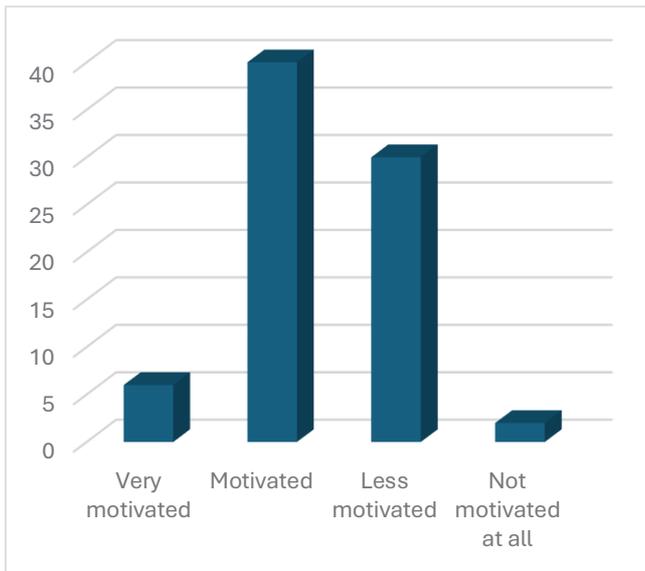


Fig.5. How motivated do you feel during your studies?

The final two questions of the questionnaire specifically addressed the place and role of the Learning Methodology course within the curriculum. One of the questions focused on the extent to which the methods and learning-support tools introduced in the course assisted students in adapting to the challenges of university life. As shown in Figure 6, in line with the initial hypothesis, the responses confirmed the value of introducing the course in the first year: according to the results, 75.6% of the participating students reported that these supportive elements had been of significant help to them.

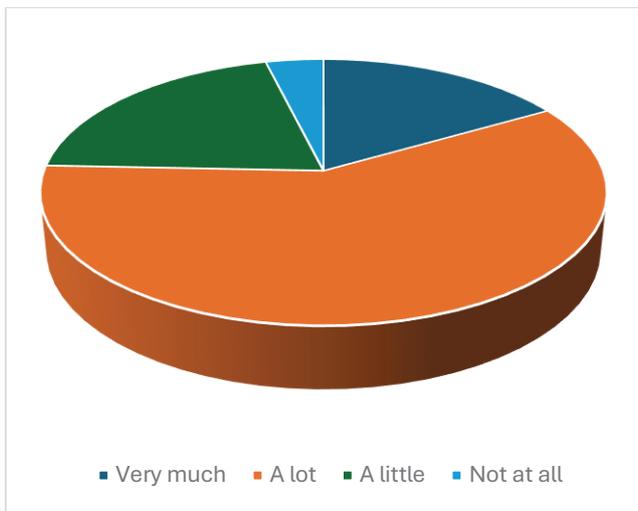


Fig.6. In your opinion, how much did the learning methodology course help you adapt to university challenges?

In another question, students were asked to evaluate the importance of incorporating learning methodology into university education. According to the responses, 27% consider it very important, 57.7% important, 11.5% less important, and 3.8% not important at all. Based on these results, it can be concluded that today’s youth express a clear demand for learning-supportive methods to be addressed within the framework of formal coursework. They seek opportunities to improve their learning strategies, discuss potential challenges, and receive answers to their questions, as shown in Figure 7.

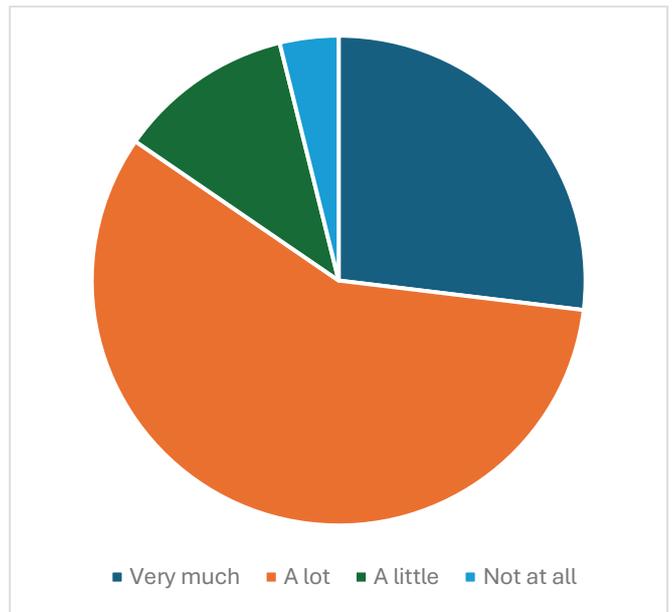


Fig. 7. How important do you think the presence of the Learning Methodology subject is in university education?

IV. SUMMARY

This study focuses on the role of learning methodology in higher education, which is becoming increasingly significant in the educational landscape of the 21st century. Learning methodology supports autonomous learning, facilitates the organization and application of knowledge, and contributes to the development of self-regulated learning, critical thinking, and lifelong learning skills. The integration of digital tools and the enhancement of IT competencies are essential in modern learning environments, especially in light of future labor market challenges.

The study also explores the issue of motivation in detail. Intrinsic motivation—stemming from curiosity and the joy of learning—leads to more sustainable and profound knowledge acquisition. In contrast, extrinsic motivational factors such as grades, scholarships, teacher recognition, or future career prospects serve as effective short-term incentives, but they prove truly beneficial when they foster the development of intrinsic motivation. Due to career transitions, technological transformations, and automation, acquiring new skills has become vital for an increasing number of students, further emphasizing the importance of learning methodology.

Conscious learning is another key focus of the study. This competence encompasses the student's ability to reflect on their own learning processes, set goals, and independently regulate their learning strategies. Self-regulated learning is a cyclical process in which learners set objectives, plan their learning activities, apply appropriate cognitive and metacognitive strategies, and evaluate their own performance. Developing metacognitive skills not only enhances academic achievement but also contributes to students’ self-confidence, problem-solving abilities, and lifelong learning capacity.

The study presents the VARK model of learning styles, which includes visual, auditory, reading/writing, and kinesthetic modalities. Visual learners benefit from graphical elements such as diagrams and charts. Auditory learners absorb information effectively through listening, such as lectures and discussions. Reading/writing learners prefer

textual information, taking notes and writing summaries. Kinesthetic learners acquire knowledge through movement and hands-on experiences, such as experimentation, modeling, or role-playing. Recognizing and applying individual learning preferences significantly increases learning efficiency.

In the quantitative phase of the study, a questionnaire survey was conducted among first- and second-year students of the Alba Regia Faculty at Óbuda University. The aim of the research was to explore the impact of the learning methodology course on students' motivation, time management habits, and adaptation to university life. Based on the responses, it can be concluded that the majority of students use time management tools and evaluate their impact on academic performance positively. Although the use of digital planners is still relatively low, it represents a promising area for future development. Most respondents feel motivated in their studies and consider the learning methodology course beneficial for adapting to the challenges of university life.

Overall, the study confirms that the application of learning methodology not only improves academic performance but also contributes to students' personal development, self-awareness, and the foundation of a successful professional career. For higher education institutions, this serves as a clear indication that the integration of learning-supportive methods and courses is not only useful but a necessary response to the educational challenges of the 21st century.

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Hands-On Learning Approaches in Teaching Pneumatics and Electropneumatics to Engineering Students

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Abstract- The integration of hands-on learning approaches into engineering education has become increasingly essential in preparing students for the practical challenges of modern industrial environments. This paper explores the application of practice-oriented teaching methods in pneumatics and electropneumatics courses within higher education. Through laboratory-based exercises, project-oriented tasks, and simulation-supported experimentation, students are provided with opportunities to bridge theoretical knowledge and real-world application. The study highlights how hands-on methodologies contribute to the development of technical competencies, problem-solving skills, and a deeper understanding of system behavior. Furthermore, the paper discusses the role of experiential learning in fostering student engagement and motivation, while addressing the pedagogical challenges of integrating practice-based approaches into curricula. The findings suggest that practice-centered education significantly enhances student preparedness for Industry 4.0 environments, where automation, control, and mechatronic systems play a key role.

Keywords - *Pneumatics, Electropneumatics, Engineering education, Hands-on learning, Practice-based teaching, Laboratory methods, Experiential learning, Project-based learning, Competence development*

I. INTRODUCTION

The rapid technological advancement and the growing complexity of automated systems require future engineers to acquire not only theoretical knowledge but also the ability to apply this knowledge in practical contexts. Within the domains of pneumatics and electropneumatics – core areas of automation and control engineering - hands-on learning approaches have proven to be particularly effective in bridging the gap between classroom instruction and industrial practice [1], [2]. As Industry 4.0 continues to reshape the technological landscape, higher education institutions face the challenge of equipping students with both technical expertise and the transversal competencies needed for professional success [3], [4].

Hands-on learning methodologies, including laboratory experiments, simulation-supported training, and practice-oriented project work, allow students to directly interact with pneumatic and electropneumatic systems [5]. This

experiential approach enhances technical understanding, improves problem-solving skills, and fosters a deeper comprehension of system behavior compared to purely theoretical instruction [6]. In addition, these methods provide students with the opportunity to test hypotheses, learn from errors, and engage in iterative problem-solving, thereby reinforcing critical engineering competencies [7].

Beyond the acquisition of technical knowledge, hands-on and project-based learning environments also deliver significant pedagogical benefits [8]. Group projects and collaborative laboratory tasks encourage teamwork, communication, and leadership, which are increasingly recognized as essential professional skills in engineering practice [9]. Students working in groups not only learn to manage complex technical challenges but also develop interpersonal abilities, such as negotiation, conflict resolution, and collaborative decision-making [10]. These soft skills are indispensable in multidisciplinary engineering contexts, where effective communication and cooperation across domains often determine the success of industrial projects [11].

Furthermore, practice-based learning motivates students by placing them in active roles within the educational process [12]. Rather than passively receiving information, learners become co-creators of knowledge as they design, build, and test pneumatic and electropneumatic systems [13]. This active engagement leads to higher retention of knowledge, greater enthusiasm for learning, and stronger preparation for professional challenges [14].

In light of these considerations, this paper examines the pedagogical advantages of hands-on learning approaches in the teaching of pneumatics and electropneumatics [15]. Particular attention is given to the integration of group-based projects and their contribution to both technical competence and soft skill development [16]. By highlighting the benefits of experiential methodologies, the study contributes to ongoing discussions on how engineering education can better align with the requirements of contemporary industry and prepare students for future technological environments [17].

II. METHODS AND PRACTICAL IMPLEMENTATION

A. Pneumatic Logic Control Exercises

The structured practice-oriented methodology begins with the design and testing of basic pneumatic control systems [18]. These exercises gradually introduce students to the fundamental principles of cylinder actuation, switching states, and safety considerations.

In the first exercise, students get to know the operation of single-acting cylinders that can perform work in only one direction. Using a 2/2 directional valve, they examine the role of initial positions, valve configuration, and spring return force. Factors influencing piston speed – such as cylinder dimensions, valve flow capacity, air pressure, and external load – are identified and controlled through throttle valves.

In the second exercise, students learn how to control a double-acting cylinder using a monostable valve. They also explore how a 4/2 or 5/2 valve controls cylinder motion. The task highlights the effect of valve return mechanisms and the interpretation of monostable states.

In the third exercise, students explore the control of a double-acting cylinder with a bistable valve, focusing on impulse signals and memory functions. Using electrically actuated 4/2 or 5/2 valves, learners gain experience with impulse-controlled actuation and memory functions of valves. The exercise stresses safe handling, as simultaneous inputs may create undefined or hazardous states.

In the fourth exercise, students study the use of three-position valves to stop cylinder movement mid-stroke and analyze safety implications. This task demonstrates the ability to stop piston movement mid-stroke, analyzing center positions such as closed-center or exhaust-center configurations. Safety aspects are emphasized, especially in applications involving lifting, pressing, or emergency stops.

The aim of these initial tasks is to consolidate understanding of valve states, safety requirements, and the relationship between mechanical motion and pneumatic control signals. For the sake of clarity, the pneumatic connections of the first and fourth exercises are shown in Fig. 1 and Fig. 2. The difference in the complexity of the connection is clearly visible. With the advent of new components and solutions, the functions are also expanded, and the time dedicated to their preparation also increases.

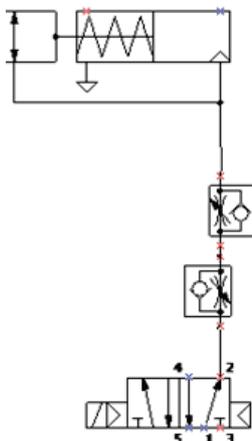


Figure 1: Control with 3/2-way valve, with placement of throttle check valves

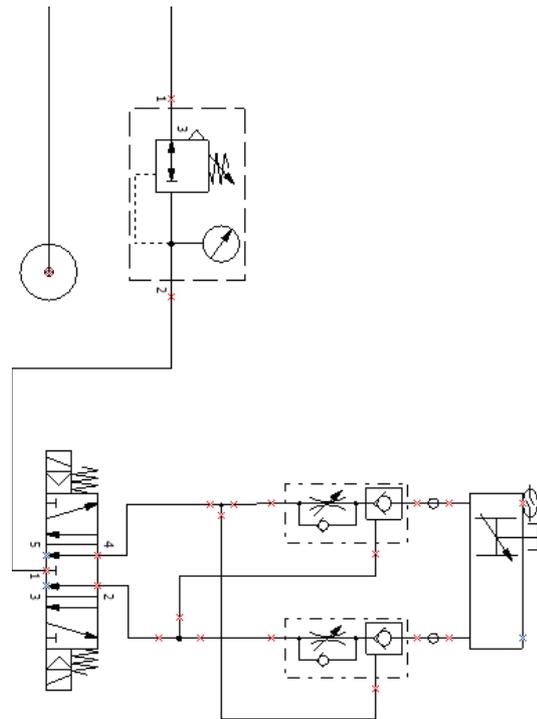


Figure 2: Pneumatic switching with 5/3 bistable valve

B. Electropneumatic Logic Control Exercises

Following the purely pneumatic tasks, students progress to electropneumatic systems where control is achieved through electrical actuation. This stage introduces the integration of switches, relays, and timers into pneumatic circuits.

In the fifth and sixth exercises, students compare direct and indirect control methods of single- and double-acting cylinders, emphasizing the role of relays. Students compare direct pushbutton control of solenoid valves with relay-assisted indirect control. The exercises highlight the advantages of indirect methods in handling higher power requirements and system reliability.

In the seventh and eighth exercises, students design latching circuits with monostable and bistable valves to maintain cylinder positions. Practical tasks focus on self-holding control solutions, where cylinder motion continues even after the pushbutton is released. Learners practice designing circuits with both electronic relays and bistable valves functioning as memory elements.

In the ninth exercise, students practice implementing time-delay control to keep cylinders in position for a defined period. Students implement delay circuits using relays and reed switches to maintain cylinder positions for a set duration. Applications include clamping, pressing, or sequential control in industrial automation.

The electropneumatic connections of the seventh and ninth exercises are shown in Fig. 3 and Fig. 4. The difference in the complexity of the connection is clearly visible. With the advent of new components and solutions, the functions are also expanded, and the dedicated time to their preparation also increases.

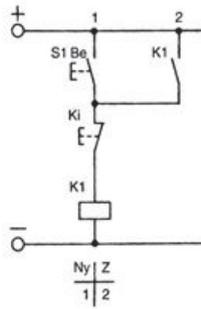


Figure 3: Self-holding circuit

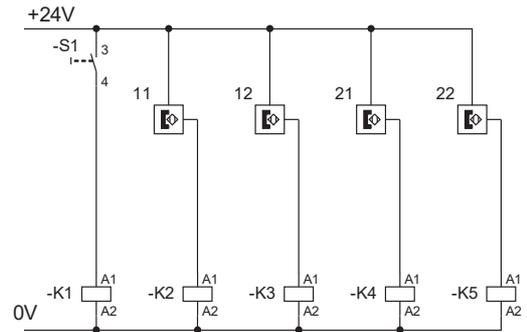


Figure 6: Sensor circuit

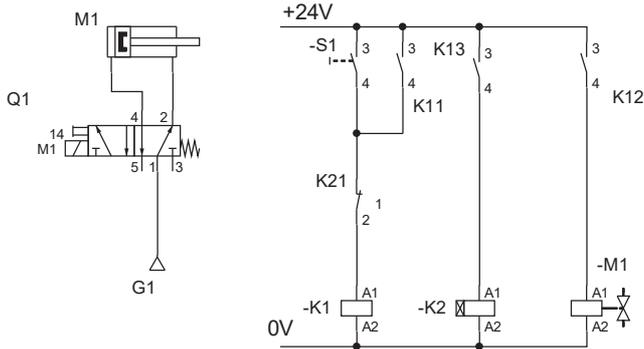


Figure 4: Monostable valve with timer

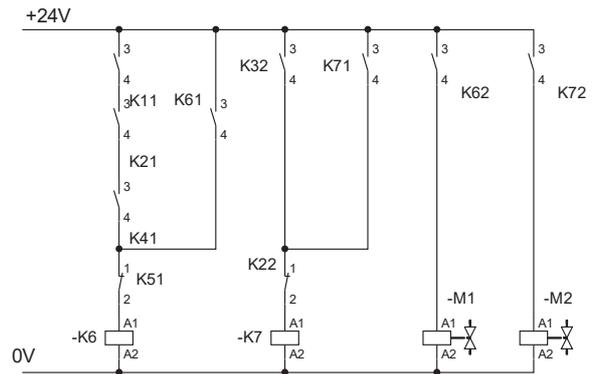


Figure 7: Complete circuit diagram of the control

C. Sequential and Process Control

Advanced exercises emphasize process-oriented control schemes where multiple cylinders operate in defined sequences. Students design and implement sequential logic using combinations of monostable and bistable valves, reed sensors, and relays.

In the tenth to twelfth exercises, students apply sequential control in feeder units, coordinating multi-step cylinder operations with sensor feedback. These tasks simulate industrial material handling processes, such as pushing and transferring workpieces between stations, see on Fig. 5. Learners design multi-step cycles (+1, +2, -1, -2) and integrate sensor feedback to ensure safe and repeatable operations, follow on Fig. 6. Both relay-based and mixed monostable/bistable valve solutions are applied (Fig. 7).

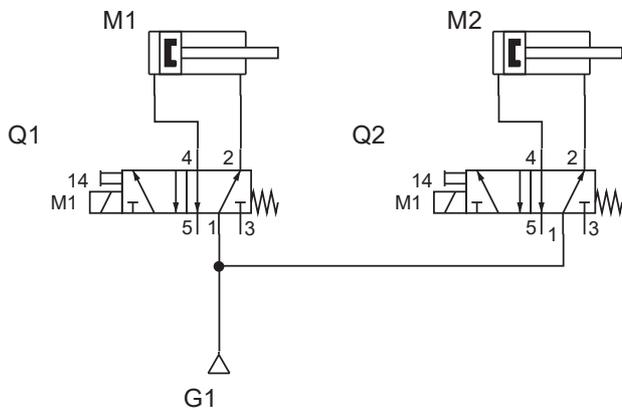


Figure 5: Pneumatic connection diagram of the dispenser

III. PEDAGOGICAL ASPECTS

The systematic inclusion of practice-based exercises in pneumatics and electropneumatics contributes significantly to engineering pedagogy by aligning teaching methods with the demands of professional engineering practice [19]. Traditional lecture-based approaches often emphasize theoretical principles but may lack sufficient opportunities for students to develop applied skills. In contrast, hands-on and project-based learning environments foster active student engagement, deeper understanding, and transferable competences [20].

Practical laboratory exercises enable students to apply theoretical knowledge in real-world contexts, reinforcing their comprehension of physical principles such as pressure, flow, and motion control [21]. Through iterative experimentation, students strengthen critical thinking, diagnostic reasoning, and system-level understanding. Furthermore, error-based learning – when students encounter and resolve unexpected circuit behaviors – encourages resilience and adaptive problem-solving [22].

A. Teamwork, Soft Skills and Motivation

Many exercises are structured as group projects, requiring students to work together in planning, building, and testing pneumatic and electropneumatic systems. Collaborative learning not only mirrors industrial project settings but also enhances communication and interpersonal skills. Students must divide responsibilities, negotiate design decisions, and integrate their individual contributions into a functional whole. This mirrors professional engineering practice, where multidisciplinary collaboration is the norm.

In addition to technical proficiency, the exercises also foster the development of a wide range of soft skills that are

essential for engineering practice. Communication skills are enhanced as students are required to explain their system designs, report experimental results, and present solutions, thereby strengthening both their technical and non-technical communication abilities. Leadership and responsibility are cultivated through group tasks, where leadership roles are often rotated, giving students the opportunity to practice project coordination, informed decision-making, and accountability. Conflict resolution skills are developed when disagreements arise over design choices, as students must engage in constructive dialogue, negotiate alternatives, and reach compromises. Moreover, time and project management abilities are strengthened through sequential exercises that demand effective scheduling, prioritization, and task allocation within the group. These competencies are highly valued by employers, as modern engineers are increasingly expected to work collaboratively across organizational, disciplinary, and cultural boundaries.

Hands-on methodologies also have strong motivational benefits. Unlike abstract lectures, laboratory and project work place students in active roles, where they can immediately observe the outcomes of their decisions and actions. The direct feedback loop between theory and practice increases intrinsic motivation and enhances knowledge retention [23, 24]. Additionally, the creative dimension of designing control solutions nurtures innovation and entrepreneurial thinking – attributes essential for modern engineering careers.

CONCLUSION

Finally, practice-based teaching in pneumatics and electropneumatics aligns directly with Industry 4.0 competence frameworks. As automation, robotics, and mechatronics advance, engineers must not only master system design but also adapt to rapidly evolving technologies. By combining technical, cognitive, and soft skill development, practice-based pedagogy ensures that graduates are better prepared for roles in advanced manufacturing, maintenance, and system integration.

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Knowledge Absorption: Development Of An Educational Platform For Project-Based Learning

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Abstract—This article discusses the development of a digital educational platform for project-based learning. It is assumed that, when combined with other innovative approaches to enhancing the educational process, project-based learning, supported by digital tools, will enhance student knowledge absorption. The purpose of this study is to develop a concept for a project-based learning platform for students. To achieve this goal, the following tasks must be addressed: 1) examine the influence of student agency on knowledge absorption; 2) determine the role structure of project-based learning actors in the knowledge absorption process; 3) formulate a concept for a project-based learning platform for students. Theories of cognitive development and knowledge absorption, the rational construction of new forms of knowledge, and methods of sequential decomposition and synthesis of complex systems are used as the methodological basis. The main results of the study include an explication of student positions, the definition of agency as a student personality trait, the determination of the role structure of project-based learning actors, the development of an integrated knowledge absorption model, and the conceptual modeling of a project-based learning platform.

Keywords—*project-based learning, knowledge absorption, subjectivity, subjective position, knowledge absorption model, educational platform*

I. INTRODUCTION

Digital transformation has impacted universities. New challenges have emerged. University-business collaboration is essential [1] [2] [3]. This requires changes in the educational process. Specifically, students need to be empowered to take a subjective position: 1) take responsibility for learning outcomes; 2) acquire knowledge purposefully; 3) understand the urgency of developing hard, soft, and digital skills.

This will enhance knowledge absorption and ensure educational outcomes. Theory must be supported by practical application [4] [5] [6]. One option is student project-based learning. This will ensure the development of students' absorptive capacities. A digital tool must be developed to support project-based learning [7] [8].

The purpose of this study is to develop a concept for a digital project-based learning platform to enhance knowledge absorption. Achieving this goal requires: 1) assessing the impact of student agency on knowledge absorption;

2) identifying the roles of project-based learning actors; and 3) developing a platform concept. The study design is structured to consistently address these objectives.

In the first part of this study, we conduct a secondary study to examine the characteristics of knowledge absorption in project-based learning. In the second part of the article, we present a conceptual model of a project-based learning educational platform for enhancing knowledge absorption. The study utilized a systematic literature review on the selected topic, a systems decomposition method to design an integrated knowledge absorption model, and a rapid prototyping method to develop the conceptual model of the project-based learning educational platform.

II. STUDENT ATTITUDE AS A KEY FACTOR IN KNOWLEDGE ABSORPTION

Knowledge absorption is defined as a learner's ability to recognize the value of new information, assimilate it, and apply it to achieve their goals [8] [9]. External and internal factors influence absorptive capacity [10] [11]. External factors help manage the effectiveness and efficiency of the learning process. Internal factors include existing knowledge, individual ability to assimilate information, level of education, experience, etc. The term "student absorptive capacity" has been updated in recent years. It is now recognized that students' knowledge absorption capacity plays a central role in learning [12] [13].

The modern generation of students is characterized by heightened individualization and a total personalization of all aspects of their lives. Students are capable of interacting through any communication channel, actively sharing information and generating new information. This requires new approaches to interaction with the instructor and dictates new requirements for the material and delivery of courses. A negative assessment of instructor-student communication hinders knowledge absorption. Here, knowledge acquisition is replaced by the process of acquiring information in various subject areas. This precludes the possibility of knowledge appropriation and hinders the process of knowledge absorption. Thus, the student's subjective position determines their educational outcomes. Table 1 presents the components of the student's subject position.

Thus, a student's subjective position is the result of their self-determination, expressed in their constructive behavior during the acquisition of knowledge and their awareness of the urgency of investing their efforts in future professional success and well-being. One option for enhancing student subjectivity is project-based learning. It ensures the application of theoretical knowledge to solving practical problems.

TABLE I. MANIFESTATION OF STUDENT SUBJECTIVITY IN THE EDUCATIONAL PROCESS

Components of the Subject Position	Manifestation in the educational process
Learning Philosophy	Acquisition of knowledge (absorption) is the foundation of a free, thinking, and independent person
Constructivism	Acquisition of knowledge (absorption) is the basis for developing a holistic picture of the world
Engagement	The student's independent efforts in the process of acquiring knowledge (absorption) ensure academic success and educational outcomes
Proactivity	The student recognizes the urgency of investing their own efforts in acquiring knowledge (absorption)
Self-determination	The student understands that acquisition of knowledge (absorption) is the foundation of professional and social development

III. BEFORE ROLES OF PROJECT-BASED LEARNING ACTORS

Project-based learning provides clear project objectives and motivates students. Each project has a time limit for completion. Students are forced to work within a strict time constraint. This sense of urgency ensures that students complete project tasks and develop hard, soft, and digital skills. This ensures educational outcomes. Thus, project-based learning fosters student agency.

Project-based learning outcomes support digital tools. They connect groups of actors in the process of solving project problems. Each actor is assigned a role. Roles define the actor's functions within the project team. The functions of the actors are defined below:

- the project task is defined by the project customer (actor A1);
- the project is implemented by the project team – the project manager (actor A2) and students (actor A3);
- the project is supported by the project administrator (actor A4).

Our university's advanced digital environment provides digital support for actors. This tool is the "Intelligent Exchange" (actor A5).

The actors' work enables the project's goals to be achieved. Actors A1, A2, and A3 sequentially complete three stages of knowledge absorption. They create new knowledge through research (knowledge creation stage). Actors A1, A2, and A3 share their results with representatives of public and private organizations (knowledge dissemination stage). Together with actors A4 and A5, they collect, process, and store the acquired knowledge (knowledge absorption stage). The stages of knowledge absorption are decomposed into processes shown in Table 2.

An important function of "Intelligent Exchange" (actor A5) is the substantive analysis of tasks incoming from customers (actor A1), their possible refinement, and

adaptation. It is necessary to ensure that the level, depth, and content of tasks, as well as the expected results of their solution, correspond to the goals of the platform and its actors, as defined by the implementers—faculty and students. Furthermore, the university itself, interested in solving various tasks, may act as a customer. Tasks may be strategic or operational in nature.

TABLE II. DECOMPOSITION OF KNOWLEDGE ABSORPTION STAGES

Knowledge Absorption Stage	Stage Process	Actors
Knowledge Creation Stage	P1. Defining Research Priorities	A1, A3, A5
	P2. Generating Ideas	A1, A2, A3, A5
	P3. Selecting a Research Direction	A2, A3, A4
	P4. Implementing Project Work	A2, A3
	P5. Assessing Readiness	A1, A5
Knowledge Dissemination	P6. Registering Intellectual Property	A2, A3, A5
	P7. Evaluating Results	A1, A4, A5
	P8. Pilot Development of the MVP	A2, A3, A5
	P9. Promoting the MVP	A1, A2, A3, A4, A5
	P10. Signing the Agreement	A1, A2, A4, A5
Knowledge Absorption	P11. Registration of property rights	A2, A3, A4
	P12. Acquisition of new knowledge and competencies	A2, A3, A4
	P13. Exchange of best practices	A1, A2, A3, A5
	P14. Entry of young specialists with relevant competencies into the labor market	A3, A5
	P15. Value creation by exchange participants	A1, A2, A3, A4

Thus, the functionality of the actors (Table 1) is condensed into an integrated knowledge absorption model is shown in Figure 4. This approach is consistent with established knowledge transfer models [14] [15].

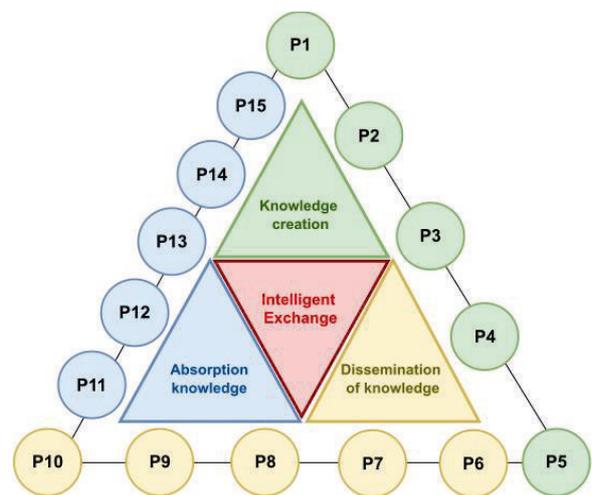


Fig. 1. Integrated model of knowledge absorption based on the educational platform of project-based learning.

The core element of the supporting structure is the project-based learning platform "Intellectual Exchange" (actor A5). It supports fifteen knowledge absorption processes. These processes are repeated cyclically at each new stage of knowledge absorption.

IV. A CONCEPTUAL MODEL OF A PROJECT-BASED LEARNING PLATFORM FOR ENHANCING KNOWLEDGE ABSORPTION

The use of modern information technologies opens up opportunities to accelerate the knowledge absorption process. This is achieved through the integration of specialized digital platforms into project-based learning.

The platform's web services reduce the labor intensity of managing and supporting project activities, creating and storing information about project tasks and client requests, completed projects, and their participants. These services support communication between learning process participants and help solve project problems.

The platform's functional specialization coordinates the actions of project teams and clients at each phase of the knowledge absorption cycle. The toolkits are presented in Table 3.

TABLE III. ROLE-BASED STRUCTURING OF PARTICIPANTS' REQUIREMENTS FOR THE PROJECT ACTIVITY PLATFORM AND ITS WORKING TOOLS

Actors	Requirements of actors for the project activity platform	Working tools of the project activity platform
Project Customer (Actor A1)	minimizing the time, it takes to establish contact with performers	-Web form for collecting requests; -Chat center; -Web form for customer responses; -Web form for contractor responses; -Web form for project managers; -Showcase of open tasks for contractors
Project Manager (Actor A2)	gaining maximum access to stored project information in real time	-Repository of completed projects; -Repository of project tasks; -Dataset repository; -Project team chat; -Chat for communication with project managers
Project Team Member (Actor A3)	obtaining up-to-date information about proposed projects	-Showcase of open tasks for performers; -Repository of completed projects; -Repository of project tasks; -Repository of datasets; -Project team chat;
Project Activity Administrator (Actor A4)	-remote communication with the project team; -real-time project information	-Chat center; -Project team chat; -Web-based response form for performers; -Web-based response form for project managers; -Repository of completed projects; -Repository of project tasks -Project support web services; -Repository of completed projects; -Repository of project tasks; -Dataset repository; -Working chat for communication with project supervisors

The platform supports the systematic absorption of student knowledge. Successful absorption is quantified by increased student agency. This is demonstrated by:

- a willingness to independently present the results of their work to the Project Custome and receive an objective and honest assessment;
- readiness to take responsibility for adopted project decisions within the framework of a personal role in the project;
- an improvement in the quality of final theses.

V. CONCLUSION

The following results were obtained during the study:

1. The influence of student agency on knowledge absorption was examined, which allowed us to determine the role structure of project-based learning actors in the knowledge absorption process;

2. The role structure of project-based learning actors in the knowledge absorption process was determined, which made it possible to formulate the concept of a project-based learning platform for students;

3. The concept of a project-based learning platform for students was developed, necessary for organizing systemic contextual learning and practice-oriented training for students in the region.

The authors found that

- the student's agency is manifested in their constructive behavior during knowledge acquisition. The use of project-based learning helps develop students' ability to absorb knowledge;
- the proposed role structure of project-based learning actors helps activate the process of knowledge acquisition and the degree of its assimilation. This ensures a higher level of absorption capacity;
- the implementation of the project-based learning educational platform supports all phases of the cyclical process of knowledge absorption and helps improve the effectiveness of the university's educational activities.

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