ACTA TECNOLOGÍA

electronic journal
ISSN 2453-675X
Volume 11
Issue 2
2025

International Scientific Journal about Technologies

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(JUNE 2025)

https://doi.org/10.22306/atec.v11i2.255 *Received: 09 Dec. 2024; Revised: 14 Apr. 2025; Accepted: 11 June 2025*

Enhancing supply chain efficiency in textiles: a deep learning approach to Industry 4.0 implementation

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Keywords: Industry 4.0, critical success factors, implementation priority, neural network, textile and clothing industry.
Abstract: Moroccan textile SMEs face increasing pressure to adopt Industry 4.0 (I4.0) technologies to enhance their competitiveness and improve their supply chains. However, a lack of clear implementation strategies, particularly regarding action prioritization, hinders their progress. This research addresses this challenge by developing an intelligent framework, grounded in Deep Learning, to guide I4.0 implementation for these SMEs. The framework leverages two key inputs: the Smart Industry Readiness Index (SIRI) dimensions, providing a structured assessment of the enterprises' current maturity across Process, Technology, and Organization, and Critical Success Factors (CSFs), identified through the DEMATEL method, capturing expert knowledge on the drivers of successful I4.0 adoption. The core of the framework is a set of specialized neural network architectures, trained to forecast the appropriate priority domain for I4.0 deployment. These specialized models, including the RNN with Attention (for Organization Priority) and the CNN-LSTM with Attention (for Technology and Process Priority), enable a nuanced and context-aware prioritization of actions. Key performance indicators show high accuracy in determining the appropriate focus area for Industry 4.0 deployment: the RNN with Attention architecture achieves 84.3% accuracy for Organization Priority, the CNN-LSTM with Attention achieves 93.3% for Technology Priority, and 83.3% for Process Priority. This data-driven and expert-informed prioritization approach offers a practical and actionable roadmap for Moroccan textile SMEs to optimize their limited resources and maximize the impact of their digital transformation efforts, ultimately contributing to a more competitive and sustainable sector.

1 Introduction

Moroccan textile SMEs face challenges in adopting Industry 4.0 (I4.0), a global initiative driving production transformation through digital technologies [1]. Technologies of Industry 4.0 are crucial in the supply chain and logistics as they enable smart automation, real-time visibility, and process optimization, thereby transforming operational efficiency and responsiveness to market demands. The lack of a clear roadmap impedes this adoption. This article proposes a Deep Learning-based intelligent framework to prioritize I4.0 actions, integrating SIRI dimensions [2] and critical success factors (CSFs) [3-7].

The Moroccan textile sector, a key economic pillar, needs enhanced competitiveness amid global pressures. I4.0 offers unique potential but demands a holistic and SME-adapted approach, aligning with Digital Morocco 2030's aims to accelerate digital transformation [8].

This research advances I4.0 in Moroccan textiles by developing an action prioritization framework that is:

- Adapted to Moroccan textile SMEs.
- Based on empirical data and rigorous analysis.
- Actionable and easy to implement.
- Dynamic and scalable.

Empowered by SIRI and CSFs, the Deep Learning models (RNN, CNN, CNN-LSTM with self-attention) identify critical action domains (process, technology, organization) for each company, considering their specific context. Using a test dataset and hyperparameter tuning, the proposed model can determine the appropriate priority for I4.0 deployment. The application of the trained neural network was discussed to ensure the success of this digital transformation project. The primary goal of this study is to obtain the necessary data and connect them (Figure1).

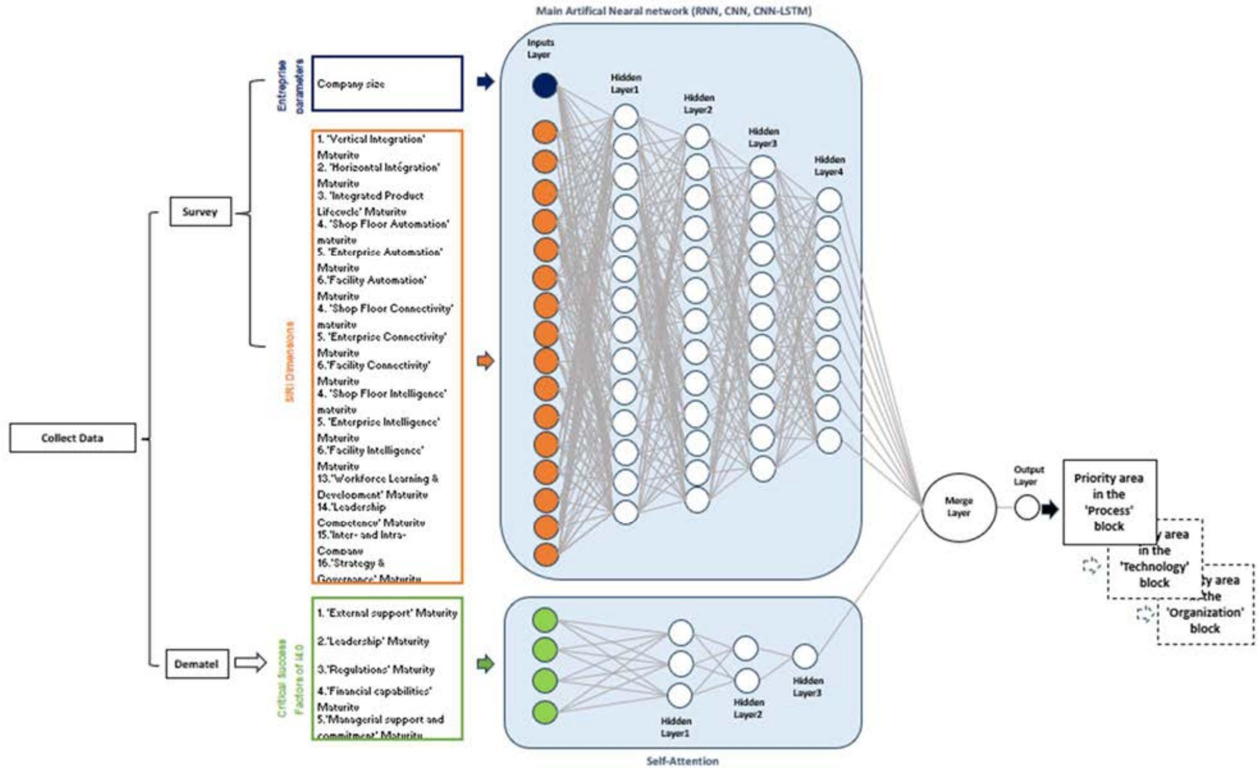


Figure 1 Neural network model input and output

Data for this research, collected from multiple sources, includes: (1) the maturity of critical success factors (CSFs) relevant to Industry 4.0, assessed separately using a Likert scale, reflecting the effort required to achieve each CSF and the extent to which it is integrated into the business [9]; (2) implementation priorities selected by the participating companies themselves; and (3) company size. The study aims to prioritize one focus area (Process, Technology, Organization) per SIRI framework building block. Due to the problem's inherent complexity and the large number of variables involved, a trained neural network model is employed to provide a data-driven solution (Figure 1). The selection of the apparel and textile industry is justified by its reliance on price competitiveness and intolerance for waste in the Moroccan context.

The manuscript's structure is as follows: Session 2 details the SIRI Framework and presents common Industry 4.0 CSFs derived from the literature. Session 3 outlines the three-step methodology: expert verification of CSFs, recording CSF and SIRI dimension maturity using a Likert scale, and utilizing a neural network to forecast the appropriate priority. In the second stage, the trained neural network uses the reliable database of CSF and dimension maturity as inputs (Figure 1) to determine priority across different company sizes. The graphical and numerical results are illustrated in Session 4, while Session 5 concludes the paper with a suggested expansion of the model to prepare for the Industry 4.0 implementation stage in a clothes company.

2 Industry 4.0 Critical Success Factors (CSFs) and SIRI framework

2.1 *Industry 4.0 Critical Success Factors*

Recognizing the importance of Industry 4.0 for manufacturing SMEs, research has extensively investigated Critical Success Factors (CSFs) through literature reviews, Delphi studies, and case studies [3-6,10]. A synthesis of this research identifies 15 key CSFs for manufacturing SMEs [11]. Further analysis using DEMATEL reveals a hierarchical structure, identifying 5 influencing CSFs that drive the remaining 10: External Support, Leadership, Regulations, Financial Capacities, and Managerial Support & Commitment. Strategically prioritizing these 5 "cause" CSFs is crucial for accurately measuring firms' I4.0 readiness and ultimately enabling successful adoption. Specifically, effectively managing these CSFs in the pre-implementation phase requires preparing them for the subsequent implementation of I4.0 dimensions as a top priority. To ensure the appropriateness of all variables for the model, data was carefully prepared, as described in the following section.

2.2 *SIRI dimensions*

Our previous study aimed to assess the Industry 4.0 maturity level of Moroccan apparel manufacturing companies and to examine disparities in their strategies for I4.0 implementation. The Singapore Industry 4.0 Readiness Index (SIRI), known as "the Index," was selected as the primary evaluation tool due to its multifaceted nature (Figure 2) [12], providing insights into both current and future improvement plans. With government support, the Index is also tailored to SMEs and MNCs, emphasizing practical application. Focusing specifically on Moroccan companies, particularly in the apparel sector, the study assesses their maturity levels. Furthermore, to prioritize areas for improved digital maturity, an empirical study was conducted to understand their current I4.0 preparedness and to suggest a path for the textile and clothing industry to bridge the gap in I4.0 evaluation campaigns. However, the SIRI priority matrix insists on concurrently implementing the three Industry 4.0 building blocks, which raises the issue of appropriate and productive sequencing in the literature [12-14]. The core challenge lies in defining the most suitable priority of the 16 SIRI dimensions or defining a combination of three focus areas (one per building block) to improve digital maturity. Therefore, a successful deployment of Industry 4.0 depends on insightful implementation priority.

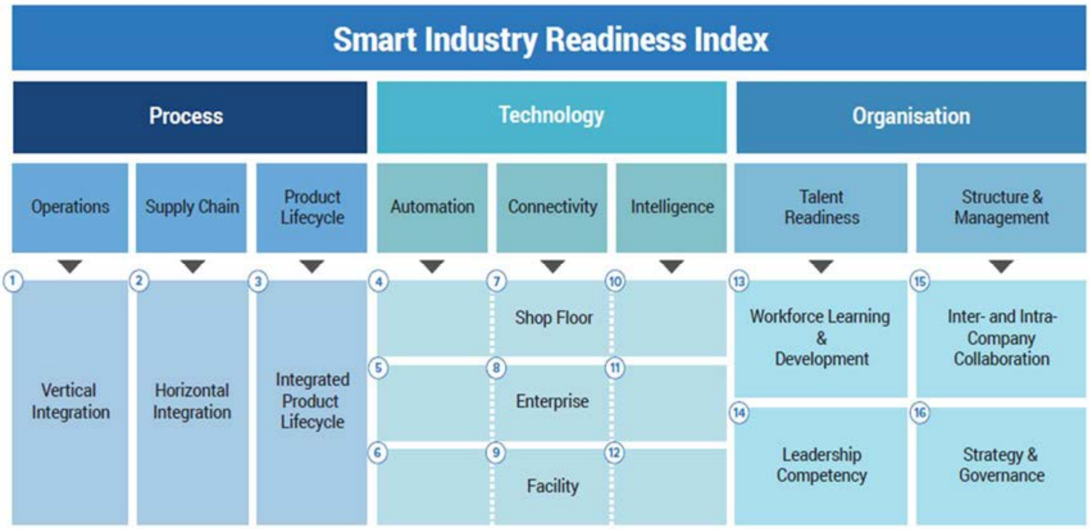


Figure 2. Singapore industry readiness index “SIRI”

3 Methods

Neural networks and deep learning algorithms offer excellent alternatives for addressing problems requiring training and data-driven insights [15]. Unlike many heuristic methods, deep learning operates without predefined calculation rules, instead learning robust relationships between focus area priorities (outputs) and various inputs: CSF maturity and SIRI dimensions maturity.

Aligned with the SIRI Framework, which structures Industry 4.0 around three building blocks – Processes, Technology, and Organization – this research aims to predict one area of intervention per building block. To achieve this, a predictive model based on three neural network models with self-attention was chosen. Self-attention empowers the model to weigh the significance of different elements in a sequence relative to each other, capturing long-range dependencies by computing attention scores based on relationships within the input sequence.

Specifically, self-attention is applied to the Critical Success Factors derived from our DEMATEL analysis. By adding Self-Attention mechanisms, these models can become even more powerful for tasks involving sequential or structured data, neural network models are popular architectures in the field of deep learning. A limitation, however, is the scarcity of extensive datasets representing real-world Industry 4.0 implementation scenarios. To address this, the results of our maturity assessment study within the Textile and Clothing sector in Morocco are used as a basis for training our model.

As depicted in Figure 1, the predictive model for the focus area priority dimensions of the three building blocks uses 22 input data and 1 output data. Among the input data, 1 relates to company size, 16 to the maturity of the SIRI dimensions, and 5 to the maturity of the Critical Success Factors. The output is linked to the focus area priority of the building block dimensions. Models are computed 3 times, each time with a different output: The priority dimensions of the Process building block, the priority dimensions of the Technology building block, and the priority dimensions of the Organization building block.

3.1 Data collection

This study measured the digital maturity of companies of varying sizes, linking their implementation strategies to different prioritized focus areas. Practitioners managing at least one Industry 4.0 project were required for participation. Data was gathered through an online survey, using the SIRI model [16] to assess digital maturity. Respondents rated the following dimensions on a scale of 0 to 5 (according to the SIRI index): Process (vertical integration, horizontal integration, integrated product lifecycle); Technology (shop floor automation, connectivity, and intelligence; company automation, connectivity, and intelligence; facility automation, connectivity, and intelligence); Organization (employee training & development, leadership skills, inter- and intra-company collaboration, strategy and governance). The average readiness index values for each dimension were gathered across the 252 participating businesses, providing an overview of I4.0 readiness for Moroccan textile and apparel manufacturers. These firms have an average readiness index of 0.95, compared to 1.04 for the average global textile company and 3.19 for global "best in class" companies [16]. Survey participants also measured the maturity of I4.0 critical success factors (CSFs) using a five-point Likert scale (1= not Mature to 5 = Totally Mature). All input variables were encoded as integers and converted to one-hot encoding format. Guided by the SIRI prioritization principle, successful Industrie 4.0 implementation requires the simultaneous development of the 3 building blocks.

3.2 Data Pré-processing

To ensure data integrity for subsequent analysis, all original data values were converted to a numeric format, and rows containing any missing values were removed. After removing irrelevant columns from the feature set, the 'Priority' column was designated as the target variable. The remaining columns were retained as primary characteristics, with a specific subset of feature columns (the CSFs maturity columns) isolated for use in the attention mechanism. The target variable was encoded into integers using Label Encoder and then transformed into a one-hot encoding format for compatibility with the classification model. To ensure a uniform scale across all features, the remaining features and attention columns were independently normalized using StandardScaler. Following normalization, Principal Component Analysis (PCA) was optionally applied to reduce dimensionality while preserving maximum information. To address class imbalance, the data was balanced using the RandomOverSampler oversampling technique. Finally, the data was partitioned into training and test sets using Train_test_split, with an 80/20 split. This rigorous pre-processing pipeline ensures clean, normalized, and correctly structured data, which is essential for enhancing the quality and performance of the trained neural network model's predictions.

3.3 Training of our three neural network-based models

Neural networks, composed of interconnected processing elements called "neurons," are powerful tools for establishing complex relationships between inputs and outputs [17]. Our neural network employs a three-layer hidden architecture, mapping *R* inputs (I) to *S* outputs (O). Each neuron sums its weighted inputs and adds a bias, feeding the result into an activation function to generate the output. The inherent complexity of neural network design stems from the numerous variables influencing training, such as the choice of learning algorithm, the number of neurons in the hidden layers, the connections between neurons and layers, the error function, and the activation function [18]. Consequently, hyperparameter tuning, a technique for selecting algorithm parameters to achieve an optimal solution dependent on these hyperparameters, is a critical step in enhancing neural network outcomes [19]. In this study, the Adam optimizer was utilized.

Table 1 Hyperparameters combinations

Model	Phase	Layer Type	parameters of layers
CNN with Attention	**Phase 1**	Conv1D	Filters: 64, Kernel size: 3, Activation: ReLU
		BatchNormalization	Standard normalization
		MaxPooling1D	Pool size: 2
		Flatten	Flattens the input
	Phase 2	Dense	Units: 128, Activation: ReLU
		Attention (Self-Attention)	Applies self-attention to features
		Flatten	Flattens the input
	Merge	Dense	Units: Number of classes (softmax output)
RNN with Attention	**Phase 1**	SimpleRNN	Units: 64, Activation: ReLU, Return sequences: True
		BatchNormalization	Standard normalization
	Phase 2	Dense	Units: 128, Activation: ReLU
		Attention (Self-Attention)	Applies self-attention to features
	Merge	Dense	Units: Number of classes (softmax output)
CNN-LSTM with Attention	**Phase 1**	Conv1D	Filters: 64, Kernel size: 3, Activation: ReLU
		BatchNormalization	Standard normalization
		MaxPooling1D	Pool size: 2
		LSTM	Units: 128, Return sequences: True
		BatchNormalization	Standard normalization
	Phase 2	Attention (Self-Attention)	Applies self-attention to LSTM output
		Flaten	Flattens the input
	Merge	Dense	Units: Number of classes (softmax output)

Table 1 details the specific hyperparameter combinations employed for our models' learning algorithm. Our setup involves setting three hyperparameters per network for the Main Network: Flattening Layers, Number of Dense Layers, Dropout, and Learning Rate (initially 0.001, dynamically reduced to 0.0005), and hyperparameters for the self-Attention Network: Number of Dense Layers, Internal Attention Layers, and Flattening Layers. Finally, a fusion layer parameter is also involved. Multiple alternatives were evaluated.

This study will employ a widely used hyperparameter optimization technique, chosen for its proven ability to deliver strong empirical results in tuning neural network performance.

4 Results and discussion

4.1 *The proposed framework*

✓ CNN with attention

The CNN with Attention model uses a Conv1D layer (64 filters, kernel size 3) followed by Batch Normalization and MaxPooling1D in its first phase to extract features from the SIRI dimensions. These features are flattened and combined with the attention-weighted DEMATEL factors. A Dense layer (128 units), and another Dense layer followed by a Softmax output layer predicts the priority domain.

✓ RNN with attention

The RNN with Attention model employs a Simple RNN layer (64 units, return sequences=True) followed by Batch Normalization in its first phase to process the SIRI dimension data sequentially. The resulting sequential features are then fed into a Dense Layer of 128 units, where they are integrated with the attention-weighted DEMATEL factors. A final Dense layer predicts the priority domain.

✓ CNN-LSTM with attention

The CNN-LSTM with Attention model combines convolutional and recurrent layers. Initially, a Conv1D layer (64 filters, kernel size 3) extracts local features from the SIRI dimensions, which are then fed into an LSTM layer (128 units, return sequences=True) followed by Batch Normalization. The learned features are then combined with the attention-weighted DEMATEL factors. A final Dense layer predicts the priority domain.

The Adam optimizer, a stochastic gradient descent method based on adaptive moments, was chosen to train the neural network due to its ability to utilize varying adaptive learning rates [19]. Combining the advantages of AdaGrad and RMSProp, Adam maintains an adaptive learning rate for each parameter by calculating moving averages of the first and second gradient moments. The learning rate was initially set to 0.001, enabling the network to retain optimal weight management at the conclusion of each batch by appropriately updating its parameters and regulating the learning speed of the model. The ReLU (Rectified Linear Unit) activation function was employed, outputting positive inputs directly while outputting zero otherwise, thereby addressing the leaky gradient issue and enhancing model learning and function. For multiclass classification, the Softmax function was used as the activation function in the output layer to predict a multinomial probability distribution. To determine the best hyperparameter combination for validation performance, a multi-step tuning process was employed. Finally, evaluating performance by accuracy enabled conclusions regarding the efficiency of our network's performance. As previously discussed, the greatest outcomes were achieved using the hyperparameter combinations.

4.2 *Evaluation of the neural network-based models*

A key indicator of overfitting is an increase in validation error. To rigorously assess the performance of our network models, we selected several popular criteria relevant to our multiclass classification task: Categorical Cross Entropy (CCE), Precision, Recall, and F1 Score [20]. Our model leverages CCE to learn to assign high probabilities to correct digits and low probability to incorrect ones. Furthermore, precision, which is directly proportional to model efficiency, evaluates the model's accuracy against real data points [20]. Ideally, the best neural network will exhibit low CCE and high accuracy.

Figures 3, 4, and 5 compare and illustrate the evolution of CCE and accuracy as a function of training epochs for the three outputs (Process Priority, Technology Priority, and Organization Priority) for each of our three models:

- **Organizational priority**

✓ CNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 89% after about 100 epochs. Training Loss decreases rapidly and continues to decrease to near 0.2.

✓ RNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 90% after about 80 epochs. Training Loss decreases rapidly and continues to decrease to near 0.2.

✓ CNN-LSTM with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 90% after about 85 epochs. Training Loss decreases rapidly and continues to decrease to near 0.2.

- **Process priority**

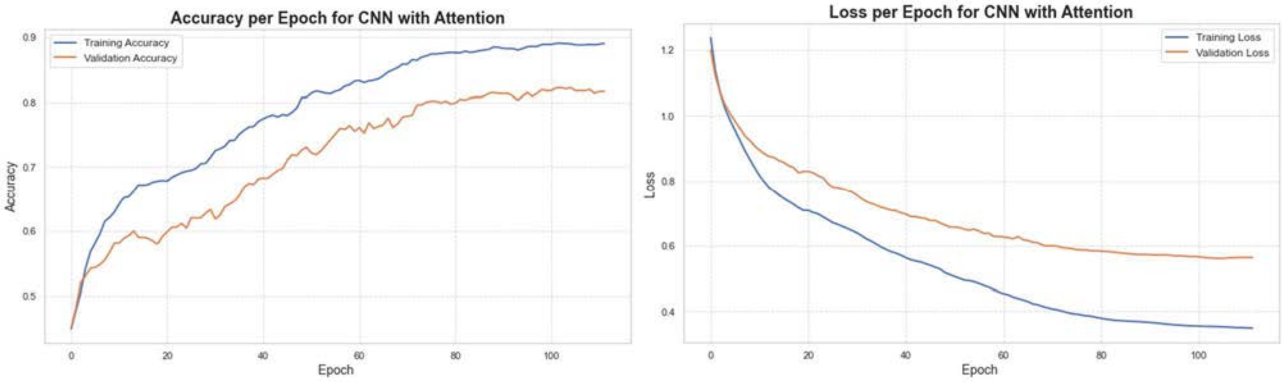
✓ CNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 80% after about 100 epochs. Training Loss decreases rapidly and continues to decrease to near 0.2.

✓ RNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 85%. Training Loss decreases rapidly and continues to decrease to near 0.2.

- ✓ CNN-LSTM with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 90% after about 150 epochs. Training Loss decreases rapidly and continues to decrease to near 0.15.

- **Technology priority**
- ✓ CNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 95% after about 150 epochs. Training Loss decreases rapidly and continues to decrease to near 0.15.
- ✓ RNN with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 93% after about 140 epochs. Training Loss decreases rapidly and continues to decrease to near 0.2.
- ✓ CNN-LSTM with attention: Training Accuracy increases rapidly early on, then continues to increase more slowly to a plateau around 97% after about 150 epochs. Training Loss decreases rapidly and continues to decrease to near 0.15.

a)



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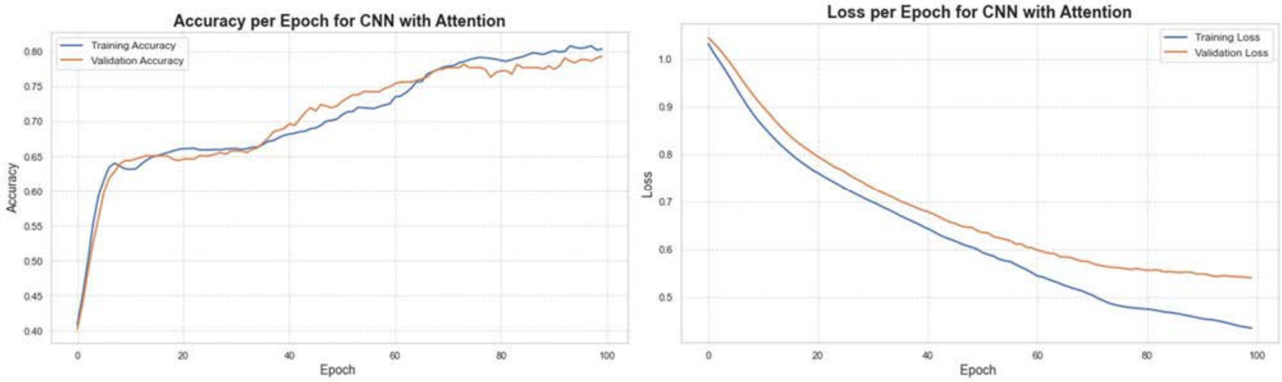

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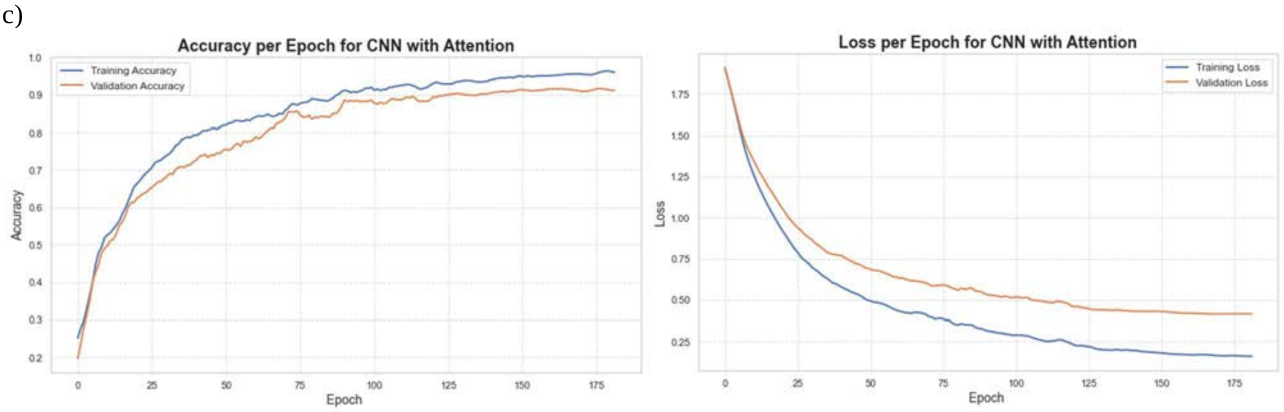
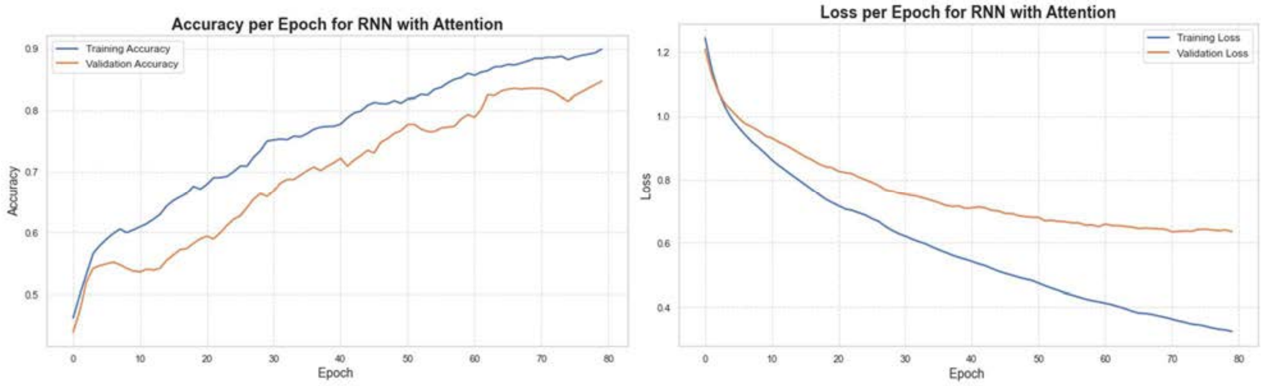
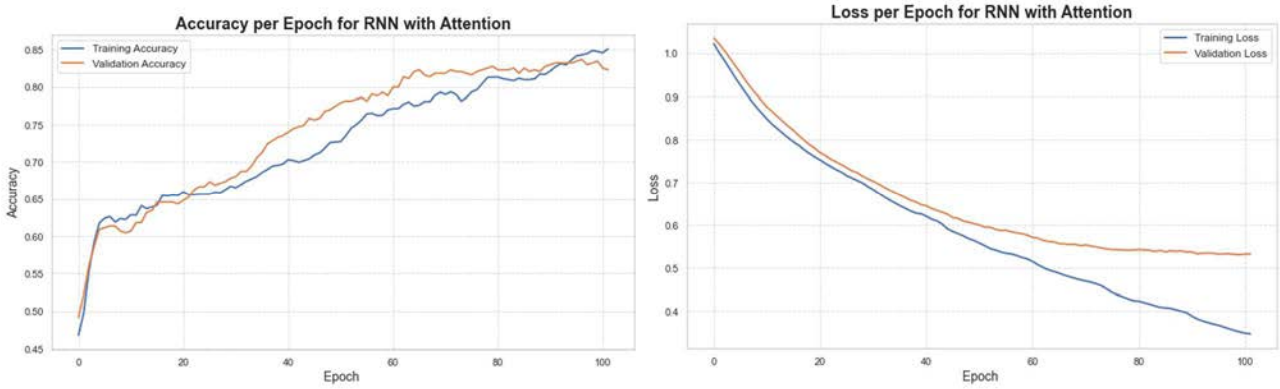


Figure 3 CNN Training curves: CCE Loss and accuracy vs. Epochs for Priority: a) Organizational priority, b) Process priority, c) Technology priority

d)



e)



f)

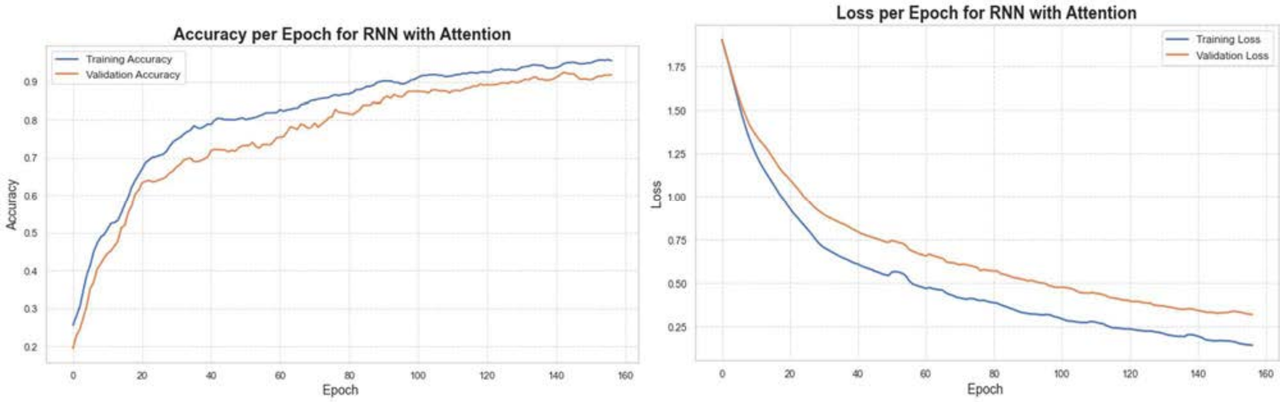
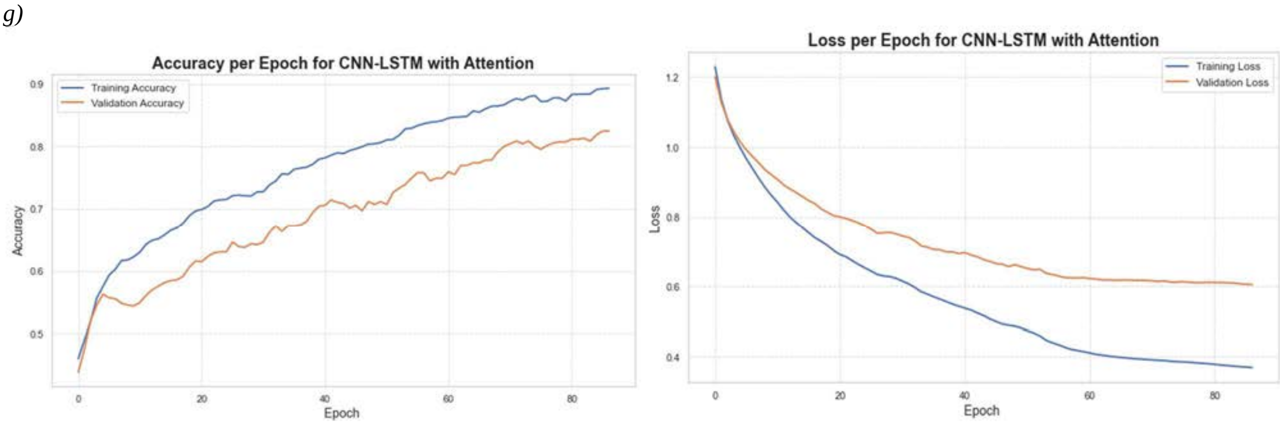
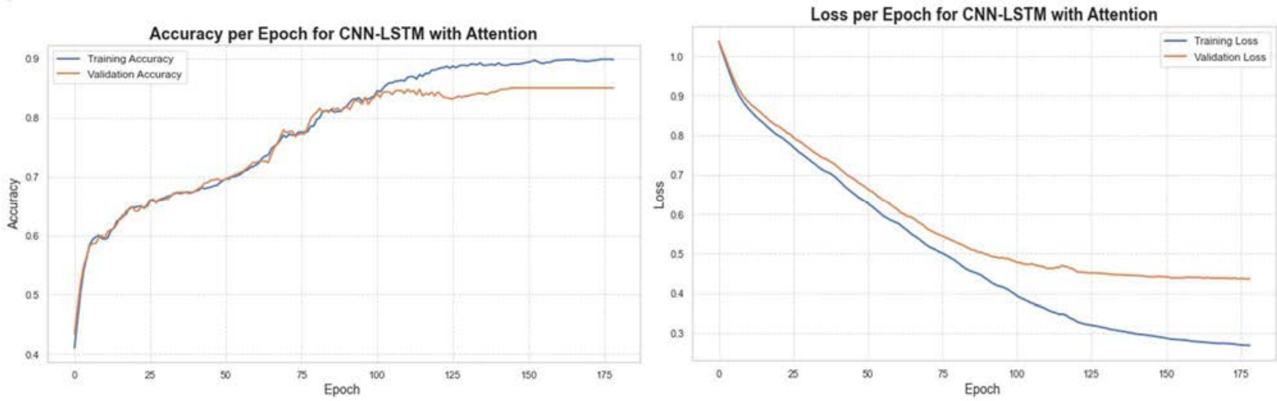


Figure 4 RNN Training curves: CCE Loss and accuracy vs. Epochs for Priority: d) Organizational priority, e) Process priority, f) Technology priority

g)



h)



i)

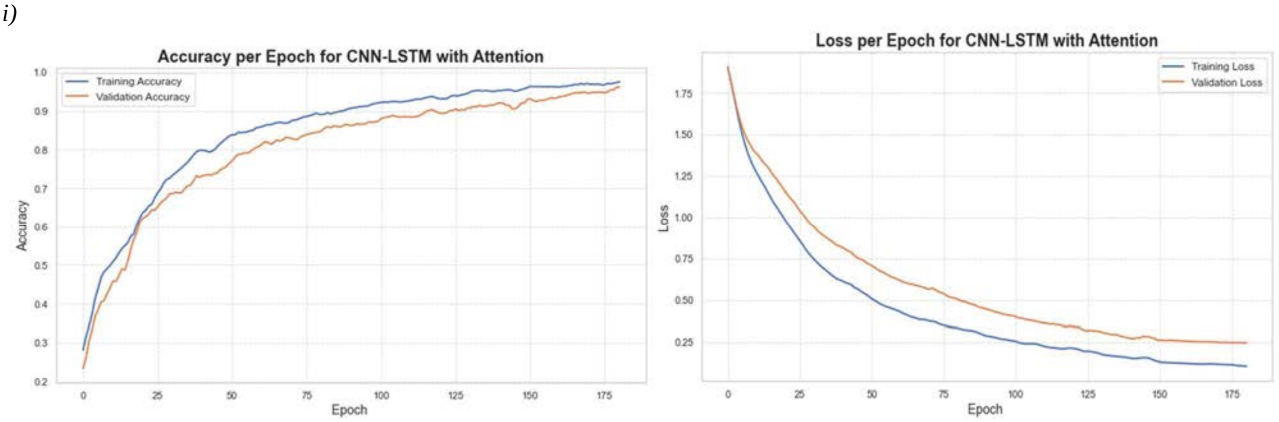


Figure 5 CNN-LSTM Training curves: CCE Loss and accuracy vs. Epochs for priority: g) Organizational priority, h) Process priority, i) Technology priority

For our models, 500 epochs were proposed as sufficient for all three outputs, yielding smoother graphs and high accuracy, reaching up to 97%. Overall, the CNN with Attention, RNN with Attention, and CNN-LSTM with Attention models demonstrated good performance in predicting the priority domain (Organization, Process, Technology) for Industry 4.0 implementation. However, CNN with Attention model generally exhibited more consistent and robust performance across the three outputs, making it a potentially more reliable choice. The CNN-LSTM with Attention model showed promise for predicting Technology Priority specifically, while the RNN with Attention model was more prone to overfitting and seemed less reliable.

In addition to classification accuracy, four measures are generally required to evaluate a neural network model's performance based on a test dataset: Test Loss (a lower measure of error is better), Accuracy (a higher percentage of correctly classified examples is better), Precision (the model's ability to avoid labeling an instance as positive that is actually negative, meaning a low false positive rate), Recall (the model's ability to find all positive instances, meaning a low false negative rate), and F1 Score (the harmonic mean of precision and recall, which provides a

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 2 Pages: 51-61 ISSN 2453-675X

balanced measure of the model's accuracy) results are shown in Tables 2, 3, and 4.

Despite the performance, and like the previous models, the CNN-LSTM with Attention model tends to perform best, but the choice of model depends on the specific priority domain. The models are significantly better at predicting Technology Priority than Process or Organization Priority, suggesting that the factors influencing technology are more easily captured. The models all need improvement but are a good starting point. To have the best model overall, we would suggest using the CNN-LSTM with Attention model. In summary, the bias and weights were initially chosen at random; subsequently, the neural network will learn on its own through the application of multiple iterations, performing forward propagation while tagging the measures highlighted in this session.

Table 2 Performance indicators of the neural network with self-attention-based models for predicting Organization priority

Model	Test Loss	Test Accuracy	Precision	Recall	F1 Score
CNN with self-attention	0.43	77.7%	77.8%	77.7%	77.3%
RNN with Attention	0.54	84.3%	85.9%	84.3%	83.8%
CNN-LSTM with Attention	0.55	84.3	84.8%	84.3%	83.7%

Table 3 Performance indicators of the neural network with self-attention-based models for predicting Process priority

Model	Test Loss	Test Accuracy	Precision	Recall	F1 Score
CNN with self-attention	0.43	77.7%	77.8%	77.7%	77.3%
RNN with Attention	0.44	82.4%	82.5%	82.4%	82.03%
CNN-LSTM with Attention	0.42	83.3%	85.5%	83.3%	82.6%

Table 4 Performance indicators of the neural network with self-attention-based models for predicting Technology priority

Model	Test Loss	Test Accuracy	Precision	Recall	F1 Score
CNN with self-attention	0.36	92.8%	92.8%	92.8%	92.2%
RNN with Attention	0.31	87.8%	87.7%	87.8%	87.4%
CNN-LSTM with Attention	0.26	93.3%	93.1%	93.3%	92.9%

5 Conclusion

Based on these observations, this paper presents a decision support tool that reliably and simultaneously determines the appropriate priority and the maturity of the SIRI dimensions for each case. Establishing a relationship between input variables (company size, SIRI dimensions, and CSF maturity) and neural network-based models was used due to the complexity of the output variables (priority of focus areas). Therefore, a trustworthy database of training and validation data was established and used to train models, refined through analysis of several neural network hyperparameters and the best combination described. The CNN-LSTM with Attention model generally performed best, although the optimal choice depends on the specific priority domain being targeted.

Performance evaluation details were presented for each output. High dependability and positive outcomes highlight the models' value as an outstanding method for solving the complex problem of deciding on a suitable focus area priority for improving Industry 4.0 maturity, based on the initial maturity and the company size.

Our study provides clothing and textile industries with a means to address the intense discussion over priorities, using standard technology and a single language. The model provides clothing managers with recommendations for successfully implementing Industry 4.0 technologies, optimizing quality, time, and resources. This generic approach can be used by any business looking to thrive in its Industry 4.0 implementation journey, and the methodology can be extended to any context and any condition.

For future research, first, similar studies can be conducted in different settings to confirm the generalization of the results. Secondly, the findings of this study could serve as a starting point for other researchers to create a roadmap for successful digital transformation by developing initiatives tailored to each priority focus area.

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Review process

Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 2 Pages: 63-73 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i2.258 *Received: 15 Jan. 2025; Revised: 18 Feb. 2025; Accepted: 16 May 2025*

The financial cost and profitability structures of the European air navigation service providers for Covid-19 period: a Monte Carlo analysis

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Keywords: Air Traffic Management, profitability, investment, Air Navigation Service Providers, European Air Space.
Abstract: Civil aviation activities are open to various ambiguities regarding air traffic flow. Small changes in political, economic and technological bodies of civil aviation can change the direction of air traffic flow and air navigation. Likewise, the civil aviation industry and its dependent branch air logistics lived through hard times during the COVID-19 period. The airlines, airports, and service providers suffered from a lot of negativities. It was an expected result for Air Traffic Flow Management to come near a financial crisis with capacity deficiencies. This paper aims to investigate this period of 2017-2021 one more time, but with a slightly different simulation methodology which assumes the period lasted for 300 years and with specific variables of Return on Investment (ROI), Return on Assets (ROA), Return on Equity (ROE), Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) in Air Navigation Service Provider Industry of Europe. According to findings, geographical location (for Central Europe, Turkey, the Mediterranean region and the United Kingdom) and the situation of states regarding development, routes and the situation of airports are the main variables of profitability and investment structures of Air Navigation Service Providers. It also concluded that the financial and economic situation of Air Navigation Service Providers in Europe cannot be changed considering these variables if this period continues for 300 years because of air the main air traffic routes and airflow order of Europe.

1 Introduction

The sustainability of a healthy financial structure is always a great hardship for airlines and air logistic companies, especially in critical and hard times such as the COVID-19 period for aviation. These critical times often occur in civil aviation such as epidemics and pandemics, security crises such as 9/11, and economic and financial crises such as oil price recessions. On the other side, the congruence of OPEX and CAPEX is subjected to different works. For instance, they are good indicators of future-oriented cost analysis, cost efficiency, cost-dependent risk orientation and performances of the current business-making activities and especially they are beneficial in producing sector-related financial information, they can give insightful views on infrastructure utilization. On the other side, ROA, ROE and ROI are good ratios of the financial value of a company and the profitability of business activities and its trading forces. If they are utilized correctly, the users (stakeholders) of them can make comparisons between financial units. Particularly in turbulent and dynamic times. At the same time, The ROA, ROE and ROI measures impact the calculation of market capitalization. For these causes, they are indispensable parts of the financial communication and public disclosures of companies in current and future possibilities.

This analysis simulates the COVID-19 period for 300 years (iteration numbers of Monte Carlo simulations) in air traffic services With more clear words, it is asked the research question is “What can the financial and economic situation be in the following 300 years if the COVID-19 period continues during that period regarding 5 important measures which are Operational Expenditures (OPEX), Capital Expenditures (CAPEX), Return on Assets (ROA), Return on Equity (ROE) and Return on Investment (ROI) in ANSP (Air Navigation Service Providers) industry of Europe?”. By doing so, it aims to show the importance of the period in terms of countries and the financial vulnerability of ANSP (Air Navigation Service Providers) industries and companies to this period empirically. Depending on their efficiency in showing the quality of earnings, EBITDA (Earnings Before Interest, Tax, Depression and Amortisation) measures are utilized for the calculations of ROA, ROE and ROI. Besides these, CAPEX and OPEX measures are so efficient in the determination of expenditures and investment power of high technology industries such as ANSP. The research serves to fill a gap regarding the utilization of simulation for 300 years in the aviation industries' financial and economic comprehension.

2 Literature review

ANSPs, by providing Air Navigation Services (ANS), establish a crucial link between airlines and airport operators, making them a significant variable in the airline industry [1]. ANSPs are highly effective in ensuring the smooth completion of flights by regulating air traffic [2] and the flow of air traffic. They offer services such as air traffic control, routing, landing, and ground operations and they support air logistic activities and air transport. Through improvements, ANSPs increase the efficiency of air traffic usage and reduce costs [3]. The activities of ANSPs are financed through air navigation service charges collected from airlines using the airspace [4]. These charges are levied on all flights using the airspace, except for demonstration flights, humanitarian aid, training, or military flights [5]. These fees are not only a revenue source for ANSPs but also play a crucial role in shaping Europe's passenger and cargo air transportation, so air traffic flow. Statistically, air navigation service charges constitute approximately 5% of the cost of each sold airline ticket [6]. The European Commission allows ANSPs to recover the costs incurred for the services they provide. However, during periods of crisis in aviation, this cost recovery approach exacerbated the crisis by dividing the costs among fewer flights, leading to regulatory changes [2]. Initially, ANSPs were only permitted to cover their costs, but later they were allowed to generate and retain profits to mitigate financial issues for airlines during crises. ANSPs derive revenues from three different types of flights: domestic, international, and transit flights [5]. ANSPs can be categorised into three different types in terms of ownership: state organisations, commercialized organisations, or privatized organisations [2]. Initially established with state involvement, ANSPs have been commercialized and privatized over time due to issues like technological equipment inadequacies, facility deficiencies, and financial resource problems [6]. Many publications have examined the impact of privatisations on ANS. It has been found that ANSPs' capabilities are directly related to the privatization processes [7]. Additionally, in the long term, the privatization of ANSPs has reduced the charges paid by users for service acquisition due to commercial competition [3,7]. The commercialisation of ANSPs began with initiatives in New Zealand in 1987, followed by Australia and Canada adopting similar methods. A state-owned business was established, refunding the government's per cent [5].

To achieve higher profitability rates in the airline market and air logistics, the focus is mainly on aircraft and human resource efficiency levels. To achieve this goal, fleet planning departments of airline companies play an active role. Fleet and schedule planners first plan an effective flight schedule design. The design of the flight schedule is the starting point of airlines' planning and operations. Flight schedule: It shows the departure-arrival time of each flight leg, the flight points when the flights take place and the fleet type to be used in the flight. Therefore, tariff components determine the competitiveness and position of the airline among its flight destinations. It is an important criterion in the continuity of the efficiency and profitability structure of the airline business. The basis of design components; is operational suitability, economic efficiency and passenger satisfaction. Airlines want to minimize flight costs and achieve safety goals with high efficiency by focusing on the aircraft utilization rate in their fleet structures, grounding times of aircraft, flight network structures, flight frequencies, occupancy rates, and on-time departure and arrival factors. In addition, airport passenger and ground services activities, where airlines' flight operations are carried out, must be established following aviation safety rules and air traffic flow management rules.

EUROCONTROL is a significant organization in the integration and coordination of ANSPs in Europe [5]. EUROCONTROL focuses on advancing the constitution of the Single European Sky (SES), a European Union initiative, to address topics such as increasing traffic levels, high ANSP service costs, heterogeneous operational practices, and air network constraints faced by the European Air Traffic Management (ATM) system. Therefore, EUROCONTROL ensures an infrastructure for air traffic flow and air logistics.

In this analysis, to measure the financial capabilities of ANSP companies across Europe, Operational Expenditures (OPEX) raised as the first important variable as an indicator of project investments [8], although they do not directly contribute to the base and they correspond to the price of keeping the business functional and involve costs of technical and commercial functionals, management [9]. So, OPEX is the main answer to the question of how an ANSP sustain its production with cost [10] which can be counted as labour, machinery and equipment, property costs and administration [11]. With its financial nature and consistency in the indication of operational strength, OPEX is the main element in business processes and the efforts toward continual process improvement for years of big industries such as Toyota [12].

On the other side, Capital expenditures (CAPEX) are utilized in the situations of disposition, modification and replacement of settled assets and it has a direct impact on the company's future cost structure [13]. Govender et al, [14] underline that capital expenditure (CAPEX) is explained as an initial investment that involves the capital costs of all fixed assets (plant and machinery) and non-fixed assets (design and commissioning costs). Other negative cash flows, classified as expenditure, are accounted for in terms of operating expenditure (OPEX), tax, and depreciation.

In a financial statement analysis, revenue can be calculated through different methodologies such as EBIT (Earnings Before Interest and Tax) and EBITDA (Earnings Before Interest, Tax, Depression and Amortisation). It is also clearly emphasised that distinctions between EBIT and EBITDA can resource from the industrial context. If this criticism is intensified here, for example, after stating their importance, It can be underlined that EBITDA can be a clear and consistent indicator for manufacturing companies against service companies [15]. It utilizes the net profit ratio to account for the main differences in variables such as ROA and EBITDA margin [16]. Lukason [17] utilises EBIT for European micro-level manufacturing companies' gain. EBIT and EBITDA measures are utilized also by Andres [18] to understand founding-family ownership structures. As he realizes his deep analysis, he underlines particularly these two typical assessments to calculate the Return on Asset (ROA) ratio. Lopez et al. [19] give place to EBITDA values to calculate ROA in the profitability structure analysis of cheese-producing companies in Spain. According to the analysis of Bouwens et al. [20], EBITDA-reporting firms are relatively smaller, more leveraged, more capital intensive, less profitable and have longer operating cycles than non-EBITDA reporting firms. It should be underlined the importance of EBITDA in financial and value-dependent decision-making.

3 Methodology

There are five important financial indicators ratios in this analysis. They are Operational Expenditures (OPEX), Capital Expenditures (CAPEX), Return on Equity (ROE), Return on Asset (ROA) and Return on Investment (ROI) of 33 ANSP companies or air traffic flow regulators. In the calculation process of ROE, ROA and ROI, EBITDA (Earnings Before Investment, Depreciation and Amortisation) values are utilised for the periods of 2017 and 2021 as argued in the writing review section. After ROE, ROA and ROI values are calculated, the values are simulated with the Pseudo Monte Carlo Method for 300 iteration numbers as in the Al-Kharusi & Murthy [21] work in Excel program by the utilization parametres of standard deviation, mean and random numbers. Their average, variance, standard deviations, maximum and minimum values are given in the following Tables. It should be noted here that there are several approaches in a huge literature regarding iteration numbers.

Monte Carlo Models are a strong tool in many fields of different sciences. It is known that the algorithms based on this method give statistical estimates for any linear function of the solution by performing random sampling of a certain random variable whose mathematical expectation is the desired function [22]. They can be utilized for risk management regarding different viewpoints [23] and even psychological research with correct sample sizes [24]. In designing a Monte Carlo analysis, the events that take their describing forces from a case or a simulation are very important. The logic of a Monte Carlo method takes a last shape with different types, Bonate [25] underlines that the sampling distribution of the model inputs should be defined a priori (before-experiment processes), for example, a normal distribution with mean μ and variance σ2. Monte Carlo simulation can explain the model repeatedly, each time drawing a different random set of inputs from the sampling distribution of the model parameters, the result of which will be a set of possible outputs and underlines the critical importance of Random Number generation or Law of Random number in computer science. At the same time, Random Number Generation is named as Pseudo-random Generators. With the utilization of a Monte Carlo Model, the users and theorists overcome the uncertainty [26]. Nonetheless, the main questions of the Monte Carlo Model are the validity of the algorithms in principle, as well as the accuracy of the results that can be obtained in practice [27]. Ferson [28] underlines the problems of the Monte Carlo methods underlying 4 important emphases; i) Like most methods based on probability theory, Monte Carlo methods are data intensive. Consequently, they usually cannot produce results unless a considerable body of empirical information has been collected, or unless the analyst is willing to make several assumptions in the place of such empirical information. ii) Although appropriate for handling variability and stochasticity, Monte Carlo methods cannot be used to propagate partial ignorance under any frequentist interpretation of probability. iii) Monte Carlo methods cannot be used to conclude that exceedance risks are no larger than a particular level. iv) Finally, Monte Carlo methods cannot be used to effect deconvolutions to solve back calculation problems such as often arise in remediation planning. Besides their advantages in the detection of optimality problems in finance [29], For Chen and Hong [30], Monte Carlo simulations utilise financial decision analysis, financial risk assessment, financial risk management, monetary portfolio management and optimisation, and financial strategic planning can be realised with Monte Carlo Methods. In classical evaluation criteria, a Monte Carlo method can be described regarding two dimensions such as data conformity of the analytical model and validation of the Mathematical model [31].

Nevertheless, the nature of the science branch and the intensity of risk gain importance in this context. In clearer words, there can be differences between social sciences, natural and engineering sciences regarding iteration numbers.

4 Findings

The main findings of 5 ratios are presented in the following 5 tables. The ROA, ROE and ROI scores are calculated by benefiting EBITDA values. At the end of the day, they are specific measures of how a company utilize its resources to create more value. These resources are assets, shareholders equity and investments. The planning, retaining and conducting of these resources are problematic, accordingly, the transformation of these resources to a return is another problem for countries. ANSPs are strategic companies for states and governments, nevertheless, the last form of Air Traffic Management is designed by regulators and authorities. In cases of emergencies, like COVID-19, the situation and results can be complex for states. The only financial resources of ANSP are flights, flight rates and air traffic flow tremendously decreased during the COVID-19 times. Without the financial aid of the states and effective financial management, the ANSP would suffer from the crisis. For this cause, the research findings gain importance for the future. Table 1 shows the OPEX (Operational Expenditures) predictions of ANSPs.

Table 1 OPEX (Operational Expenditures) Predictions

	Mean	Variance	Standart Dev.	Maks	Min	Country
Albcontrol	-2122.9	391038.1	625.330432	-76.451	-4141.38	Albania
ANS CR	-2886.31	235535	485.3194542	-1298.05	-4452.85	Czech
Fintraffic	-64.8163	65.51633	8.094216134	-38.3273	-90.9433	Finland
ARMATS	-3508.2	131902.3	363.1835421	-2319.65	-4680.5	Armenia
Austro Control	-237.861	2509.53	50.09521175	-73.9204	-399.561	Austria
Avinor Flysikring	-1892.48	29727.01	172.4152213	-1330.05	-2448.14	Norway
BULATSA	-167.104	739.2837	27.18977156	-78.4085	-254.73	Bulgaria
Croatia Control	-551.04	954.8651	30.90089091	-450.238	-650.626	Croatia
DFS	-1096.71	4860.481	69.71714964	-869.287	-1321.39	Germany
DHMI	-2.7939	0.839766	0.91638747	0.195435	-5.7472	Türkiye
DSNA	-1481.54	625.4605	25.009209	-1399.7	-1562.27	France
EANS	-16.8469	2.379024	1.542408352	-11.7992	-21.8256	Estonia
ENAIRE	-655.968	3239.44	56.91607706	-469.705	-839.684	Spain
ENAV	-608.849	336.0728	18.33228849	-548.855	-668.023	Italy
Hungaro Control	-27.0253	1.68764	1.299092019	-22.774	-31.2186	Hungary
IAA	-147.708	22.82272	4.777313116	-132.074	-163.128	Ireland
LFV	-2625.68	118639.3	344.4404987	-1498.47	-3737.49	Sweden
LGS	-21.5436	5.119026	2.262526477	-14.1393	-28.8467	Latvia
LPS	-53.4893	173.0126	13.15342497	-10.4435	-95.9466	Slovak republic
LVNL	-218.627	417.3622	20.42944413	-151.77	-284.57	Netherlands
MATS	-19.0232	1.271858	1.12776698	-15.3325	-22.6634	Malta
M-NAV	-824.124	13441.64	115.938102	-444.707	-1198.36	North Macedonia
MOLDATSA	-157.529	407.4915	20.18641843	-91.4676	-222.688	Moldova
NATS	-619.046	708.1677	26.61142021	-531.958	-704.944	United Kingdom
NAV Portugal	-175.179	118.9642	10.90706989	-139.485	-210.385	Portugal
NAVIAIR	-976.292	17789.18	133.3760681	-539.807	-1406.81	Denmark
Oro Navigacija	-21.1055	9.791503	3.129137685	-10.8652	-31.2059	Lithuania
PANSA	-761.572	4089.291	63.94756783	-552.298	-967.986	Poland
ROMATSA	-893.877	478.6348	21.87772387	-822.28	-964.495	Romania
Skyguide	-392.148	532.3552	23.07282469	-316.64	-466.624	Switzerland
Slovenia Control	-30.3055	5.95982	2.441274319	-22.3162	-38.1856	Slovenia
SMATSA	-7.81604	0.404822	0.636255861	-5.73384	-9.86978	Serbia and Montenegro

Operational expenditures (OPEX) show a clear picture of an ANSP's activities-dependent expenditures regarding maintenance, rent, equipment, inventory costs, marketing, payroll, insurance, step costs, and funds allocated for research and development. According to our Monte Carlo analysis results on OPEX, all of the countries will be subjected to operational costs for the research period. On the other side, developed countries and aviation countries such as Germany, France, Sweden, Denmark and Norway Air Navigation Service Providers (ANSP) tend to realise more operational costs than other countries. Table 2 shows the results of the simulation for CAPEX (Capital Expenditures) predictions.

Table 2 Capex (Capital Expenditures) Predictions

	Mean	Variance	Standart Dev.	Maks	Min	Country
Albcontrol	-506.866	137840.9	371.269312	708.1457	-1705.27	Albania
ANS CR	-802.549	36419.25	190.8382711	-178.014	-1418.55	Czech
Fintraffic	-3.92931	3.997475	1.999368752	2.613806	-10.383	Finland
ARMATS	-525.01	80084.19	282.9915104	401.1049	-1438.47	Armenia
Austro Control	-26.5795	27.45004	5.239278551	-9.43346	-43.4911	Austria
Avinor Flysikring	-385.298	10065.92	100.329069	-58.0151	-708.634	Norway
BULATSA	-23.8277	38.64405	6.216434145	-3.54912	-43.8617	Bulgaria
Croatia Control	-95.3044	867.4117	29.45185362	0.770208	-190.22	Croatia
DFS	-103.522	227.4705	15.08212451	-54.3225	-152.128	Germany
DHMI	-1.20216	0.076174	0.275996413	-0.30183	-2.09162	Türkiye
DSNA	-198.966	174.0552	13.19299933	-155.791	-241.551	France
EANS	-4.64272	6.798849	2.607460232	3.890426	-13.0592	Estonia
ENAIRE	-97.0058	400.7021	20.01754357	-31.4966	-161.62	Spain
ENAV	-105.988	333.6197	18.26525808	-46.2137	-164.946	Italy
HungaroControl	-5.46383	2.454688	1.566744494	-0.33652	-10.5211	Hungary
IAA	-19.2714	90.05216	9.489581859	11.78415	-49.9023	Ireland
LFV	-393.803	19172.69	138.4654995	59.33794	-840.749	Sweden
LGS	-5.56363	4.661598	2.159073381	1.502132	-12.5328	Latvia
LPS	-6.08391	7.77634	2.788608991	3.042065	-15.0851	Slovak republic
LVNL	-49.0818	316.8936	17.80150437	9.175243	-106.542	Netherlands
MATS	-2.0796	1.826213	1.35137457	2.342896	-6.44164	Malta
M-NAV	-62.9512	3706.096	60.87771038	136.2765	-259.456	North Macedonia
DATSA	-12.7091	92.8623	9.636508634	18.82721	-43.8144	Moldova
NATS	-137.565	1749.455	41.82648664	-0.68365	-272.574	United Kingdom
NAV Portugal	-23.5221	40.75122	6.383668308	-2.63094	-44.1276	Portugal
NAVIAIR	-102.377	556.6386	23.59319011	-25.1662	-178.532	Denmark
Oro Navigacija	-4.95836	17.43561	4.175596526	8.706648	-18.4366	Lithuania
PANSA	-165.723	2218.34	47.099252	-11.5863	-317.752	Poland
ROMATSA	-44.1069	147.5389	12.14656119	-4.35618	-83.3142	Romania
Skyguide	-59.6107	279.5858	16.72082066	-4.89032	-113.583	Switzerland
Slovenia Control	-2.73126	4.432513	2.105353313	4.158699	-9.52703	Slovenia
SMATSA	-2.04063	0.064881	0.25471692	-1.20704	-2.86282	Serbia and Montenegro

Capital Expenditure (CAPEX) includes the investment projects of ANSP companies. According to our Monte Carlo results developed and aviation countries realized investments in the projects of ANSP-related activities such as Germany, France, Sweden, Denmark and Norway Air Navigation Service Providers (ANSP). ROA (Return on Assets) predictions are given in Table 3.

Table 3 ROA (Return on Asset) predictions

	Mean	Variance	Standart Dev.	Maks	Min	Country
Albcontrol	0.122947	0.002305	0.048011183	0.280068	-0.03203	Albania
ANS CR	0.036821	0.015504	0.124513749	0.444304	-0.36509	Czech
Fintraffic	0.077852	0.065852	0.256615935	0.917651	-0.75047	Finland
ARMATS	0.199721	0.035039	0.187187735	0.81231	-0.40449	Armenia
Austro Control	0.018968	0.005323	0.07295958	0.257734	-0.21654	Austria
Avinor Flysikring	0.004397	0.005462	0.073905408	0.245483	-0.23378	Norway
BULATSA	0.096997	0.001098	0.033141901	0.205109	-0.00981	Bulgaria
Croatia Control	0.117879	0.008307	0.091143357	0.415197	-0.17585	Croatia
DFS	0.045992	0.000905	0.030083454	0.144127	-0.05096	Germany
DHMI	0.214072	0.01309	0.114411505	0.587293	-0.15465	Türkiye
DSNA	0.123595	0.001476	0.038417267	0.249319	-0.00041	France
EANS	0.176904	2.379024	1.542408352	5.224573	-4.80176	Estonia
ENAIRE	0.048282	0.101237	0.318177794	1.089547	-0.97875	Spain

ENAV	0.114381	0.000882	0.029696301	0.211565	0.018526	Italy
HungaroControl	0.055496	0.026256	0.162037759	0.58578	-0.46754	Hungary
IAA	0.083237	0.002139	0.046254117	0.234608	-0.06606	Ireland
LFV	0.040208	0.000816	0.028561529	0.133678	-0.05198	Sweden
LGS	0.095908	0.017025	0.130479105	0.522912	-0.32526	Latvia
LPS	0.017585	0.013974	0.11821327	0.404448	-0.36399	Slovak republic
LVNL	-0.03276	0.026543	0.162921717	0.500412	-0.55865	Netherlands
MATS	0.06555	0.007447	0.086296104	0.347962	-0.213	Malta
M-NAV	0.03589	0.040386	0.200963157	0.69356	-0.61279	North Macedonia
MOLDATSA	0.03783	0.025847	0.160769479	0.563963	-0.48111	Moldova
NATS	0.114474	0.001333	0.036506266	0.233944	-0.00336	United Kingdom
NAV Portugal	0.046009	0.001428	0.037793199	0.16969	-0.07598	Portugal
NAVIAIR	0.064777	0.00079	0.028108212	0.156764	-0.02595	Denmark
Oro Navigacija	0.081961	0.004502	0.067099796	0.301551	-0.13463	Lithuania
PANSA	0.116673	0.008256	0.090862924	0.41403	-0.17662	Poland
ROMATSA	0.027912	0.004569	0.067597634	0.249131	-0.19028	Romania
Skyguide	0.013969	0.016954	0.130208358	0.440088	-0.40632	Switzerland
Slovenia Control	0.0457	0.074755	0.273413565	0.94047	-0.83684	Slovenia
SMATSA	0.027242	0.012887	0.113522085	0.398753	-0.33919	Serbia and Montenegro

According to ROA results, The ANSPs of Armenia, Türkiye, and Poland realized high asset utilization regarding EBITDA. ROE (Return on Equity) prediction results are shown in Table 4.

Table 4 ROE (Return on Equity) predictions

	Mean	Variance	Standart Dev.	Maks	Min	Country
Albcontrol	0.143047	0.003228	0.056814884	0.328978	-0.04034	Albania
ANS CR	0.028638	0.028195	0.167913317	0.578149	-0.51336	Czech
Fintraffic	0.078425	0.883347	0.939865591	3.154219	-2.95532	Finland
ARMATS	0.232204	0.046132	0.214782706	0.935099	-0.46108	Armenia
Austro Control	1.55244	12.80519	3.578433567	13.26318	-9.99822	Austria
Avinor Flysikring	0.031695	0.469784	0.685407639	2.267557	-2.17721	Norway
BULATSA	0.117189	0.001727	0.041554099	0.252742	-0.01673	Bulgaria
Croatia Control	0.200961	0.024763	0.157361876	0.714289	-0.30618	Croatia
DFS	-0.14898	0.01559	0.124860562	0.258331	-0.55137	Germany
DHMI	0.307747	0.021539	0.146760251	0.786492	-0.16523	Türkiye
DSNA	0.353489	0.004522	0.067246032	0.573557	0.136428	France
EANS	0.369796	0.121409	0.34843746	1.510089	-0.75491	Estonia
ENAIRE	0.02138	0.222579	0.47178258	1.565331	-1.50146	Spain
ENAV	0.216205	0.001747	0.041796933	0.352989	0.08129	Italy
HungaroControl	0.046271	0.05713	0.239018974	0.828482	-0.72525	Hungary
IAA	0.150617	0.0069	0.08306864	0.422467	-0.11752	Ireland
LFV	-0.97314	0.401276	0.633463557	1.099921	-3.01787	Sweden
LGS	-0.34428	2.108381	1.452026402	4.407604	-5.03121	Latvia
LPS	-2.94201	34.20485	5.848491402	16.1977	-21.8201	Slovak republic
LVNL	0.639071	0.966004	0.982854879	3.855552	-2.53344	Netherlands
MATS	0.099283	0.029575	0.171974781	0.662086	-0.45583	Malta
M-NAV	0.035346	0.058141	0.241124632	0.824448	-0.74297	North Macedonia
MOLDATSA	0.049451	0.031921	0.178663568	0.634143	-0.52725	Moldova
NATS	0.29885	0.003407	0.058369826	0.48987	0.11044	United Kingdom
NAV Portugal	0.149641	0.014145	0.118931551	0.538855	-0.23425	Portugal
NAVIAIR	0.111629	0.001672	0.040887001	0.245435	-0.02035	Denmark
Oro Navigacija	0.104294	0.007945	0.089133389	0.395991	-0.18342	Lithuania
PANSA	0.210895	0.024161	0.155438453	0.719581	-0.29084	Poland
ROMATSA	1.221329	26.15086	5.11379073	17.95667	-15.2852	Romania
Skyguide	0.009219	0.085911	0.293105029	0.968431	-0.93688	Switzerland

Slovenia Control	-0.07361	0.43374	0.658589689	2.081685	-2.19944	Slovenia
SMATSA	0.019692	0.038909	0.197253926	0.665223	-0.61701	Serbia and Montenegro

According to ROE results, the ANSPs of Austria, Romania, Italy, and Croatia realised high equity utilisation regarding EBITDA. ROI (Return on Investment) prediction results are given in Table 5.

Table 5 ROI (Return on Investment) predictions

	Mean	Variance	Standart Dev.	Maks	Min	Country
Albcontrol	-2.94104	19.34883	4.398730612	11.4542	-17.1395	Albania
ANS CR	-0.28274	1.279359	1.131087445	3.418843	-3.93373	Czech
Fintraffic	-0.47002	19.49105	4.414866908	13.97803	-14.7206	Finland
ARMATS	-8.93839	89.63603	9.467630731	22.04527	-39.4985	Armenia
Austro Control	0.741382	4.890644	2.21148	7.978648	-6.39695	Austria
Avinor Flysikring	0.018397	1.030456	1.01511381	3.32979	-3.25307	Norway
BULATSA	-0.27974	1.285521	1.133808043	3.418843	-3.93373	Bulgaria
Croatia Control	-0.58755	4.525179	2.127246716	6.351723	-7.44314	Croatia
DFS	-1.07768	0.655478	0.809615963	1.563359	-3.68687	Germany
DHMI	-2.24606	1.251536	1.118720527	1.40331	-5.85142	Türkiye
DSNA	-1.08128	0.073853	0.271759217	-0.19192	-1.95847	France
EANS	-1.42266	1.559276	1.248709803	2.663858	-5.45331	Estonia
ENAIRE	0.020227	0.241147	0.491066994	1.627288	-1.56487	Spain
ENAV	-3.04413	0.311606	0.558216555	-1.21732	-4.84597	Italy
HungaroControl	-1.17612	0.268692	0.518355126	0.520244	-2.84929	Hungary
IAA	-0.48121	0.454357	0.674059988	1.724709	-2.65698	Ireland
LFV	0.594221	0.292871	0.541175559	2.365267	-1.15261	Sweden
LGS	0.105532	0.022929	0.151423736	0.601079	-0.38324	Latvia
LPS	0.026364	0.023507	0.153320715	0.52812	-0.46853	Slovak republic
LVNL	0.241947	2.421094	1.555986522	5.334052	-4.78055	Netherlands
MATS	-1.35314	2.839509	1.68508428	4.161444	-6.79235	Malta
M-NAV	-2.61935	26.74442	5.171500655	14.30484	-19.3122	North Macedonia
MOLDATSA	1.248736	28.70816	5.358000042	18.78327	-16.0461	Moldova
NATS	-4.02552	32.00269	5.657091968	14.48781	-22.2858	United Kingdom
NAV Portugal	-0.79436	0.400074	0.632514039	1.275599	-2.83602	Portugal
NAVIAIR	-0.5463	0.793294	0.8906703	2.368497	-3.42125	Denmark
Oro Navigacija	-1.66601	3.135605	1.770763958	4.128972	-7.38178	Lithuania
PANSA	-1.91655	6.142803	2.47846781	6.194454	-9.91668	Poland
ROMATSA	0.088222	0.036086	0.18996277	0.709892	-0.52495	Romania
Skyguide	0.04633	2.400141	1.549238945	5.116353	-4.95439	Switzerland
Slovenia Control	-0.71803	18.09658	4.254007864	13.20359	-14.4493	Slovenia
SMATSA	-0.33218	1.125599	1.060942399	3.139851	-3.75674	Serbia and Montenegro

According to ROI results, the ANSPs of the Netherlands, Latvia, and Slovak Republic realized high investment utilization regarding EBITDA.

5 Discussion and conclusions

As seen in the findings section, geographic locations have great importance for Air Navigation Service Providers' financial profitability and investments. Considering the reality that taxes and fees for air carriers have deep impacts on the economic structures of these state-based companies, flights and route selection are determinative variables. Besides these geographical location impacts, tax and fee regimes of countries, correct and definite high-technology selection should be the subject of more detailed analysis. In the Figure 1, there is an explanation of European air traffic. According to it, Central Europe, Turkey and Mediterranean region and the United Kingdom are important geographies in the defining of air transport and air transit ways of the European continent, therefore the findings are expected and desired results regarding financial profitability and investment (expenditure) structures.

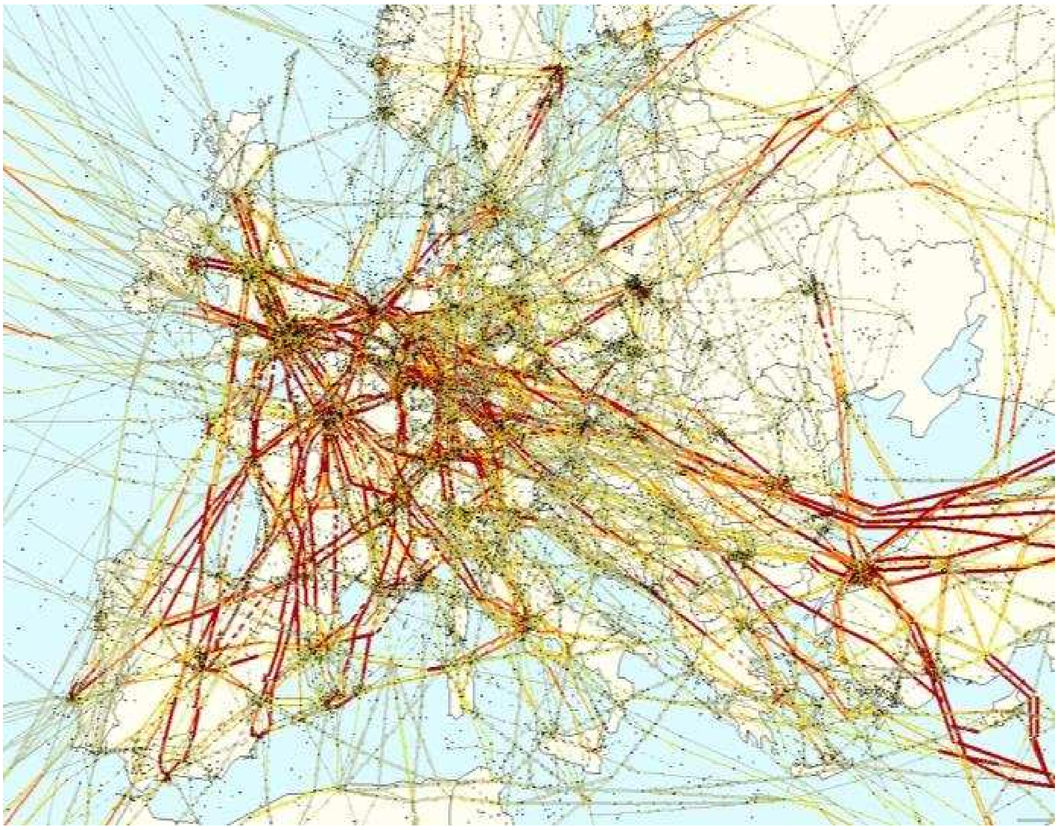

Figure 1 Density plot of European air traffic
Source: [32]

On the other hand, the airport's utilization in the European Zone approves the importance of findings one more time considering the busiest airports of the European continent in Figure 2. Nevertheless, the timespan of 2017-2022 is so complex because of the reality of Covid-19. Depending on the reality of cargo transportation and cargo-related logistics, the busy airspace regions did not feel the crisis but profitability and investment values are so low for other countries. The research presents that some states governed the crisis period better than other states regarding OPEX, CAPEX, ROA, ROE and ROI. If this period continues for 300 years, the results should be so dark for other countries that are out of the main routes regarding Air Navigation Services.

It should be underlined that the governance and management of ANSP structures, air traffic flow and capacity management and air logistic activities have a lot of dynamics, today there are different projects in the air traffic governance body of Europe such as SESAR (Single European Sky Air Traffic Management Research). As in every logistic and civil air transportation activity, standardization [33], and the selection of correct, efficient, effective routes can be considered some important items for future safety, securely, environmentally friendly, and economic [34]. To ensure these items one by one, more widespread and comprehensive governance is a necessity in political, legal, technological and economic dimensions. Another important dilemma is to prepare for the next crisis.

As stated many times, civil air transportation and air logistics can be easily manipulated with a crisis structure because of its highly political, technological and economic components. The states should protect their independence in the air, while they protect their financial and technological development regarding air flow and air traffic. Therefore, the balance between the value of the main determinants (safety and security) of civil aviation and profit-seeking motivation will gain importance in the next steps for Europe which suffered from international conflicts such as the Russia-Ukraine War, and the Israel-Palestine War and competition with the United States and China. The existence of AIRBUS should be used as an opportunity and all European countries should benefit from the advantages of AIRBUS climate like in the example of BOEING and the impacts of the BOEING networks on the world. The effective contribution of African and Asian governments to civil air transportation and air logistics activities will change the main routes and the financial position of ANSPs in Europe.

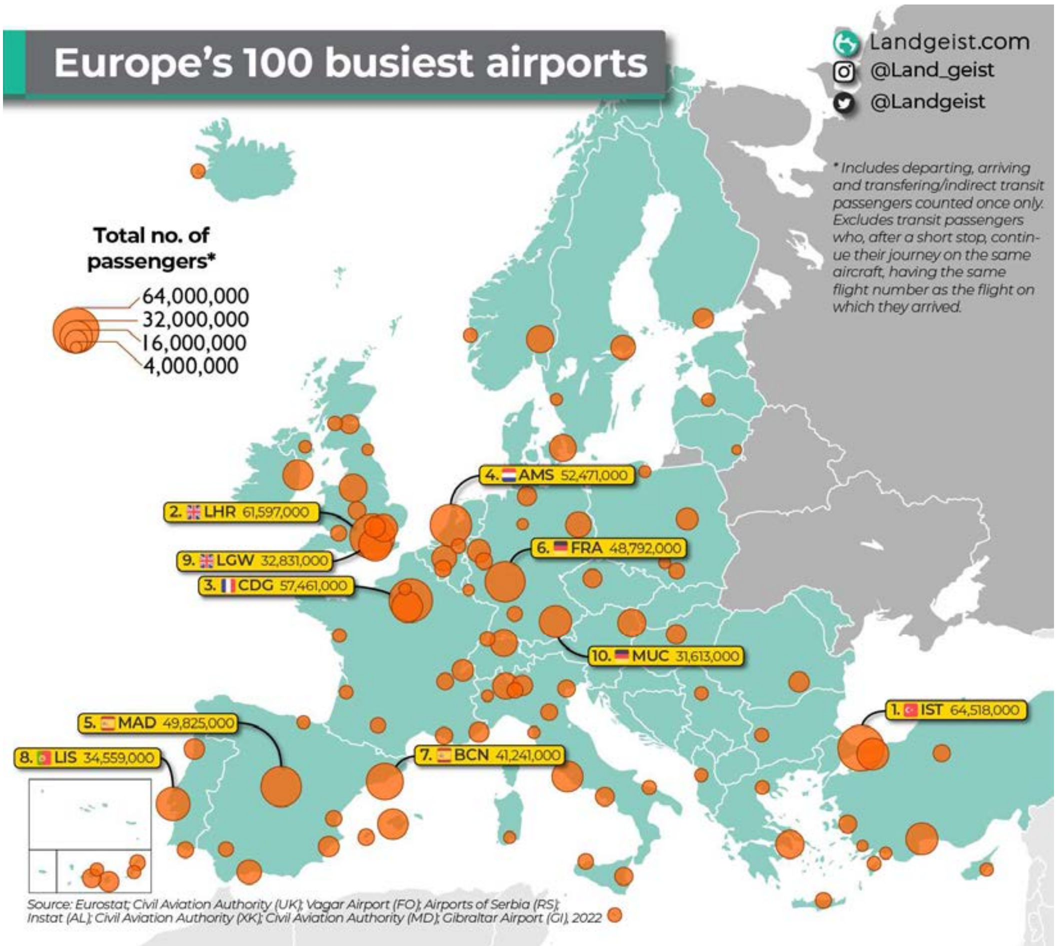

Figure 2 Europe's 100 busiest airports
Source: [35]

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Review process

Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 2 Pages: 75-79 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i2.272 *Received: 06 Mar. 2025; Revised: 10 May 2025; Accepted: 13 June 2025*

Hydrogels as bioactive scaffolds in biomedical engineering

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Keywords: hydrogels, scaffolds, biomedical engineering.

Abstract: Hydrogels have emerged as promising biomaterials in tissue engineering and regenerative medicine due to their high water content, biocompatibility, and structural similarity to the extracellular matrix (ECM). This article reviews the design principles and key physicochemical properties of bioactive hydrogels—such as stiffness, porosity, degradation rate, and biochemical functionalization—and their role in modulating stem cell behavior and guiding tissue regeneration. Special attention is given to the influence of hydrogel mechanics on mechanotransduction, strategies for controlled drug and growth factor delivery, and surface functionalization to enhance cell adhesion and lineage-specific differentiation. Recent advances in dynamic, cell-responsive, and degradable hydrogels are highlighted as crucial developments for creating personalized and clinically relevant scaffolds.

1 Introduction

Tissue engineering and regenerative medicine rely on biomaterials that can support cellular processes and guide tissue regeneration. Hydrogels, due to their high water content, biocompatibility, and ECM-mimetic properties, have been extensively studied as scaffolding materials for stem cell culture, drug delivery, and regenerative therapies (Figure 1). Hydrogels can be tailored to mimic the mechanical, chemical, and biological properties of native tissues, making them highly suitable for applications in bone, cartilage, neural, and cardiovascular repair [1].

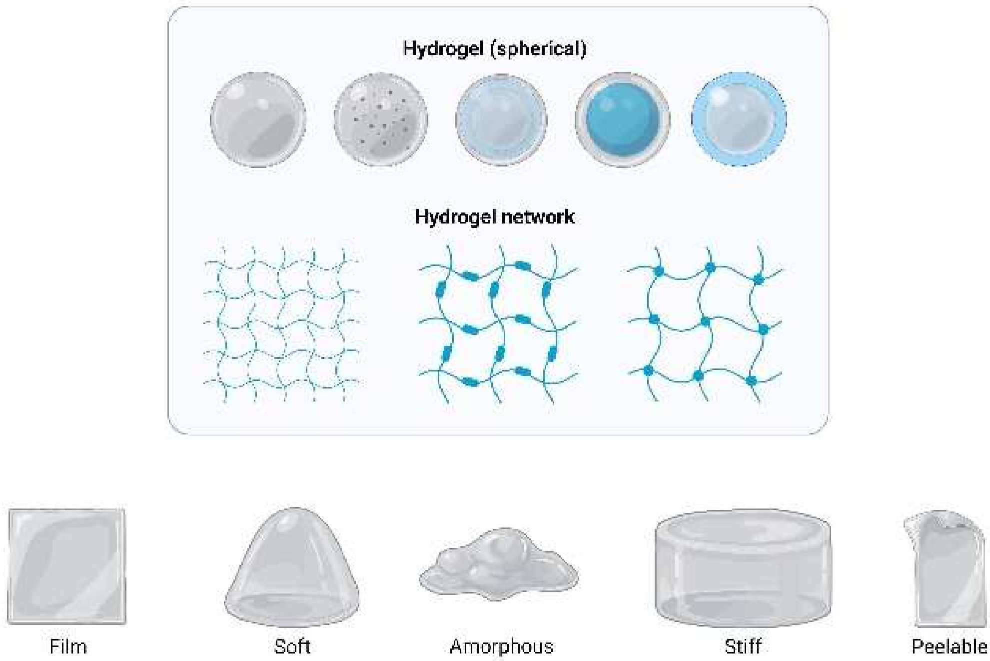

Figure 1 Illustration of various hydrogel forms and structures, showcasing spherical hydrogels, hydrogel networks, and different physical states, including film, soft, amorphous, stiff, and peelable hydrogels (created with Biorender.com)

Stem cells, including mesenchymal stem cells (MSCs), embryonic stem cells (ESCs), and induced pluripotent stem cells (iPSCs), require a biologically active environment that provides essential cues for proliferation, differentiation, and lineage commitment. Hydrogels can be engineered to include bioactive peptides, growth factors, and extracellular matrix (ECM) proteins that interact with cell surface receptors and regulate downstream signaling pathways. Furthermore, the mechanical and topographical properties of hydrogels, such as stiffness, porosity, and degradation rates, influence cell migration, morphogenesis, and tissue remodeling [2,3].
This article explores the design principles of bioactive hydrogels, their influence on stem cell behavior, and their role as scaffolds for regenerative medicine.

2 Physicochemical properties of hydrogels and their role in cell behavior

The success of hydrogel-based scaffolds in tissue engineering and regenerative medicine relies on a precise balance of physicochemical properties that influence mechanical integrity, cellular interactions, biodegradability, and bioactivity. These properties dictate how stem cells adhere, proliferate, and differentiate, ultimately determining the scaffold's effectiveness in tissue repair [4]. The ability to fine-tune hydrogel stiffness, porosity, degradation rate, and biochemical functionalization allows researchers to mimic the extracellular matrix (ECM) and optimize hydrogel performance for specific biomedical applications. The mechanical properties of a hydrogel define how it responds to external forces and cellular traction, playing a crucial role in stem cell mechanotransduction [5]. Hydrogels with higher stiffness can direct stem cells toward osteogenic differentiation, while softer matrices support neuronal and chondrogenic differentiation. The swelling capacity and water retention ability of a hydrogel influence nutrient diffusion and metabolite exchange, affecting stem cell survival and metabolic activity [6]. Additionally, porosity and permeability regulate cell migration, vascularization, and tissue infiltration, which are essential for long-term regenerative success. Degradation kinetics, governed by enzymatic and hydrolytic processes, determine how well a hydrogel integrates with host tissue and whether it degrades at a rate synchronized with new tissue formation [7]. Finally, biochemical modifications, such as growth factor incorporation, ECM protein conjugation, and peptide functionalization, enhance the hydrogel's ability to interact with stem cells and stimulate lineage-specific differentiation [8,9]. Each of these physicochemical properties is interconnected, requiring a multifactorial approach when designing hydrogel scaffolds for biomedical applications [10].

2.1 Hydrogel stiffness and mechanotransduction

The stiffness or elastic modulus (E) of a hydrogel plays a pivotal role in cell fate determination. Stem cells are highly sensitive to the mechanical properties of their microenvironment, a phenomenon known as mechanotransduction, where extracellular mechanical signals are converted into biochemical responses that regulate gene expression.

- Soft hydrogels (0.1–1 kPa) mimic the mechanical properties of brain and neural tissues, promoting neuronal differentiation of stem cells.
- Intermediate stiffness (5–15 kPa) is optimal for muscle and soft tissue engineering, supporting myogenic differentiation.
- Stiff hydrogels (>30 kPa) resemble bone ECM, directing osteogenic differentiation of MSCs.

Mechanotransduction is mediated through integrin clustering, focal adhesion formation, and cytoskeletal tension. Advances in dynamic hydrogels that can alter stiffness in response to external stimuli allow for the sequential differentiation of stem cells into multiple lineages, mimicking native tissue development [11,12].

2.2 Porosity and diffusion properties

Porosity is a defining characteristic of hydrogels that influences cell infiltration, vascularization, and nutrient diffusion. The pore size, distribution, and interconnectivity of a hydrogel impact stem cell migration, tissue integration, and oxygen exchange, which are essential for successful tissue regeneration [13].

Hydrogels with small pores (<5 µm) create a dense matrix that restricts cell penetration, making them suitable for barrier applications such as wound dressings or cartilage protection. In contrast, macroporous hydrogels (50–300 µm) provide a scaffold architecture that supports cell migration, vascular network formation, and tissue remodeling. Highly porous hydrogels allow for rapid diffusion of oxygen, glucose, and bioactive molecules, preventing the formation of hypoxic cores in engineered tissues [4,14].

The ability to tailor hydrogel porosity is crucial for different tissue engineering applications:

- Bone and cartilage scaffolds require interconnected macropores (50–200 µm) to facilitate osteoblast infiltration and extracellular matrix deposition.
- Neural scaffolds benefit from aligned microchannels that guide neuronal extension and synapse formation.
- Cardiovascular applications utilize anisotropic pore networks to mimic the aligned fiber structure of blood vessels, ensuring proper endothelialization and vascular patency [15,16].

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 2 Pages: 75-79 ISSN 2453-675X

Modern fabrication techniques such as cryogelation, porogen leaching, and 3D bioprinting enable precise control over pore size, gradient structuring, and multi-layered hydrogel designs that replicate the hierarchical organization of native tissues [15,17].

2.3 Biodegradability and enzymatic degradation

Biodegradability is an essential feature of hydrogels that allows for progressive tissue replacement as the scaffold degrades. The rate of degradation must be finely tuned to match tissue formation dynamics; premature degradation can compromise scaffold integrity, while excessive persistence may lead to fibrotic encapsulation [18,19].

Natural hydrogels such as collagen, gelatin, hyaluronic acid, and fibrin degrade enzymatically, mimicking native ECM turnover. The incorporation of matrix metalloproteinase (MMP)-sensitive sequences allows for cell-driven degradation, where stem cells secrete enzymes to remodel the hydrogel in a biologically controlled manner. Synthetic hydrogels like polyethylene glycol (PEG), polyvinyl alcohol (PVA), and polyacrylamide degrade via hydrolytic cleavage, which can be engineered to occur over weeks to months, depending on polymer crosslinking density [20].

Cell-responsive degradation is crucial for applications such as:

- Bone tissue engineering, where slow-degrading hydrogels (weeks to months) support prolonged mineral deposition and osteogenesis [21].
- Wound healing applications, where fast-degrading hydrogels (days to weeks) enable rapid epithelialization and matrix remodeling [22].
- Drug delivery systems, where degradation is programmed to release growth factors, cytokines, or small molecules in a time-controlled manner.

Recent innovations in bio-orthogonal click chemistry and self-healing hydrogels have enabled the development of smart degradable materials that respond to cellular enzymatic activity, pH changes, or inflammatory signals, allowing for on-demand scaffold remodeling [23,24].

3 Functionalization strategies for bioactive hydrogels

3.1 Growth factor and drug delivery

Hydrogels act as localized delivery platforms for bioactive molecules, providing sustained release of growth factors, cytokines, and small-molecule drugs. Controlled delivery of vascular endothelial growth factor (VEGF) promotes angiogenesis, while bone morphogenetic proteins (BMP-2, BMP-7) induce osteogenic differentiation in bone regeneration. Encapsulation of anti-inflammatory agents such as dexamethasone or IL-10 can modulate immune responses to implants, improving graft survival [25,26].

Authors Hu et al. developed a hyaluronic acid (HA) and chitosan-based hydrogel (OHA-CMC) with antibacterial and hemostatic properties, created through a Schiff base reaction. They incorporated nanotechnologically-modified curcumin (CNP) and epidermal growth factor (EGF) into the hydrogel. The resulting OHA-CMC/CNP/EGF hydrogel demonstrated significant antioxidant, anti-inflammatory, and migration-promoting effects in vitro. The hydrogel released curcumin in the early phase of wound healing to reduce inflammation and oxidative stress, while EGF was gradually released to support later stages, such as proliferation and extracellular matrix (ECM) remodeling. In a diabetic skin defect model, the hydrogel significantly enhanced wound healing, including re-epithelialization, granulation tissue formation, and skin appendage regeneration, showcasing its potential as a therapeutic dressing for diabetic wounds [27].

3.2 Surface functionalization with ECM proteins

Hydrogel surfaces can be modified with ECM-derived proteins such as fibronectin, laminin, vitronectin, and collagen to enhance cell adhesion and integrin signaling. Peptide motifs such as RGD (Arg-Gly-Asp) improve cell attachment, while IKVAV and YIGSR sequences promote neuronal differentiation [4]. Álvarez-López et al. developed a biofunctionalization strategy using covalent immobilization of extracellular matrix (ECM)-derived oligopeptides on Ti-6Al-4V surfaces via activated vapor silanization (AVS) and EDC/NHS crosslinking chemistry. The immobilization was stable, even under chemical denaturing conditions. The modified surfaces enhanced mesenchymal stem and progenitor cell attachment, spreading, and growth, supporting chondro- and osteo-regeneration. Additionally, the method improved adhesion of a neural cell line with poor anchorage properties, demonstrating its versatility [28].

4 Discussion

The physicochemical properties of hydrogels—including stiffness, porosity, degradation, and biochemical functionalization—serve as the foundation for their biological performance in tissue engineering. The ability to engineer hydrogels with tunable mechanics, precise pore architectures, and controlled degradation profiles allows researchers to create microenvironments that guide stem cell behavior and tissue regeneration. Advances in dynamic and stimuli-responsive hydrogels further enhance the adaptive capabilities of these biomaterials, opening new frontiers in personalized regenerative medicine, bioactive implant coatings, and controlled drug delivery systems. Future research must continue optimizing these parameters to bridge the gap between laboratory-scale hydrogel design and clinical translation, ensuring their successful integration into regenerative therapies [8,27].

5 Conclusion

Hydrogels represent a transformative class of biomaterials in biomedical engineering, offering a versatile platform for tissue regeneration, drug delivery, and stem cell modulation. Their tunable physicochemical properties—such as stiffness, porosity, degradability, and biofunctionalization—allow for precise control over the cellular microenvironment, enabling the engineering of scaffolds that mimic native extracellular matrices. Continued advancements in smart and stimuli-responsive hydrogels, along with biofabrication techniques, hold significant promise for translating these materials from bench to bedside. However, challenges related to mechanical stability, biocompatibility, and large-scale manufacturing must be addressed to fully realize the clinical potential of hydrogel-based therapies. Future research should focus on integrating multidisciplinary approaches to design next-generation hydrogels that can dynamically adapt to biological cues and promote personalized regenerative outcomes.

Acknowledgement
The state grant agency supported this article with projects KEGA 018TUKE-4/2023 and VEGA 1/0403/25.

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Review process

Single-blind peer review process.

Acta Tecnología - International Scientific Journal about Technologies
Volume: 11 2025 Issue: 2 Pages: 81-85 ISSN 2453-675X

https://doi.org/10.22306/atec.v11i2.279 Received: 31 Mar. 2025; Revised: 12 May 2025; Accepted: 03 June 2025

Application of digital twin using discrete event simulation in intralogistics processes

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Keywords: digital twin, discrete event simulation, AMR, intralogistics processes.
Abstract: As technology advances, companies are increasingly using technologies such as computer simulations and digital twins. These technologies enable monitoring, analyzing and optimizing the performance of processes in real time. They are also very useful in testing new ideas. This article presents the concept of using discrete event simulation as an integral part of the digital twin in the design and analysis of intralogistics processes. The authors propose using the Enterprise Dynamics discrete event simulator to create a digital twin of the AMR vehicle. For this purpose, they assessed the available technologies and the possibilities of their cooperation within the proposed digital twin.

1 Introduction

The Fourth Industrial Revolution has caused more and more companies to use modern technologies in their organization. This is due to the fact that companies require continuous improvement of their processes in order to ensure competitiveness, efficiency and adaptability. This trend is quite noticeable in the manufacturing industry. One of the most popular and increasingly widely used is the digital twin technology [1-4]. This technology is defined as a virtual representation of a real object, system or process. A digital twin is created using real-time data and simulation and modeling techniques. The purpose of their creation is to reproduce the behavior, characteristics and functioning of physical counterparts. They are used in the area of continuous improvement of production and intralogistics processes and increasing operational efficiency. There are a number of benefits associated with their use. These include the ability to predict exceptional situations, better risk management, the ability to monitor the process in real time and identify bottlenecks. The use of a digital twin (DT) also contributes to cost reduction and more complete achievement of sustainable goals. Another benefit of using a digital twin is the ability to effectively manage resources. Their monitoring contributes to making rational business decisions [5]. A digital twin also allows companies to introduce new products to the market earlier. A digital twin is therefore a tool that can support decision-making by providing full insight into real data and processes. In parallel with the growing interest in and application of digital twins in the industrial sector, computer simulations are used. One of the most popular simulation modeling methods used in the area of production processes is discrete event simulation (DES). The method is very useful in the analysis of structured workflows, optimization of resource allocation and identification of bottlenecks in the analyzed processes. This method is also used to create digital twins, becoming their integral part. DES tools take over the role of a digital twin, performing simulation software tasks on real-time data generated by IoT devices embedded in the physical twin [6,7].

The aim of the article is to propose a concept of using the DES tool as a digital twin in intralogistics processes.

The structure of the article is as follows. The introduction presents the characteristics of digital twins. The second chapter contains a review of the literature in the area of digital twins and discrete event simulation. It also presents examples of implementing digital twins in industry. The third chapter Methodology presents the proposed research methodology. In the next chapter, the authors propose a concept of using the DES simulator as an integral part of the digital twin. The whole article ends with a summary.

2 Literature review

Digital technologies enable precise monitoring and control of production and intralogistics processes, which contributes to their higher efficiency. Their use enables ongoing detection and elimination of potential irregularities. One of the increasingly commonly used tools are discrete event simulators and digital twins. Process modeling using discrete event simulation concerns processes in which all changes in the simulation model are represented by events that occur when specific conditions occur. Since discrete event simulation models are dynamic in nature, the current value of the simulated time should be tracked as the simulation progresses. It is also necessary to use a mechanism to shift the simulated time from one value to another. This results from the fact that time is subject to abrupt changes depending on the occurrence of discrete events [8-11]. There are many discrete event simulation tools available on the market. The most popular include: Arena, AnyLogic, Enterprise Dynamics, FlexSim, Simio, Plant Simulation, Simul8 [12]. In most cases, the software available on the market allows building models from ready-made objects, for which it is necessary to determine input parameters, relationships with other objects and the correctness of the process course. After building a simulation model, simulation experiments are carried out on it. The process taking place during the experiment is a reflection of the real process. Studying the process using simulation models allows for analyzing the characteristics of the process taking place during the simulation experiment and allows for determining the impact of input parameters on the behavior of the modeled process. During the process simulation, a larger number of experiments can be carried out using different values of input parameters. The obtained results, which are most often presented in the form of reports and graphs, are subject to further analysis and allow for selecting the optimal solution. The developed simulation model can also be subject to continuous modifications, and for the new versions of the model, subsequent simulation experiments can be carried out.

Simulation models in their basic form don't include automated data flows between the digital and physical worlds. In most cases, they use historical data [13]. They are characterized by varying degrees of staticity, because in some models, data can be manually updated. On the other hand, a digital twin has a close connection between the digital and physical worlds. Its characteristic feature is complete bidirectional data exchange (Figure 1).

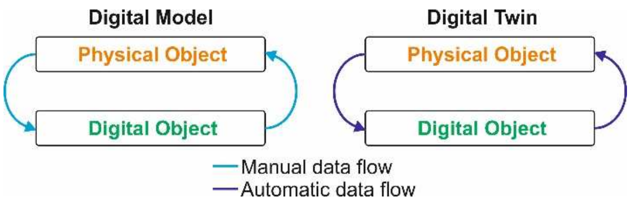

Figure 1 Data flow in the digital model and digital twin

Continuous two-way communication and data flow between the digital and physical worlds is possible thanks to the use of IoT sensors. These are devices used to collect and transmit data over the Internet using technologies such as wireless technology, big data, cloud computing. The authors of [6] note the strong connection between DES and DT. They pointed out that future research in this area should focus on solving the limitations and meeting the requirements for integrating DES with DT, and then on using DES and DT as a single technology.

Currently, some researchers have taken up the topic of the possibility of using discrete event simulators within the digital twin. One of such works is [14]. Its authors developed a DES system that uses online data to improve forecasts. The Flexsim software used by the authors, which allows real-time connections with servers, databases, and even PLC controllers. The object of the research was the production process and the conducted studies showed that DES provided more accurate forecasts of future performance and unforeseen problems in the near future compared to the forecasts of traditional DES using only historical data. An example of using the Flexsim discrete event simulator to implement a digital twin in a production environment is also presented in [15]. The authors of the work [16] proposed a digital twin solution based on a discrete event simulator and RFID technology. They tested the proposed solution on the example of warehouse management. The authors of the work [17] also dealt with the topic of integration of DES and DT technologies. In this case, the authors used Tecnomatix software. The digital model developed in this package was connected to the physical object using KEPServerEX and TSN technologies. The authors of [18] also presented a proposal to use DES technology in DT. Using the Simio software as an example, they tested the proposed solution for supporting decisions in the area of logistics processes taking place in the enterprise.

Based on the literature review, the authors decided to propose a concept of using the DES technology as an integral part of the digital twin in the design and analysis of intralogistics processes.

3 Methodology

The article proposes a concept of a digital twin based on discrete event simulation enabling the design and analysis of intralogistics processes. For this purpose, a conceptual design was developed, which is the first stage of the design process, which aims to develop general assumptions for the future solution. As part of the developed concept, a literature review was conducted and the current state of knowledge on the integrity of digital twins and discrete event simulators was assessed. Existing technological solutions were also reviewed. The scheme of the developed concept is presented in Figure 2.

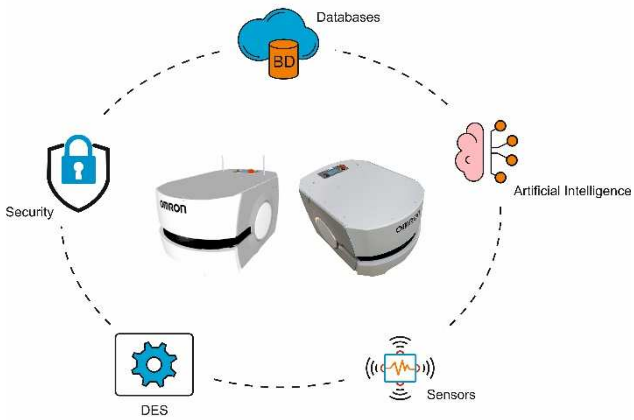

Figure 2 Concept of using a digital twin with a DES simulator in intralogistics processes

The assumptions of the proposed concept are presented in the next chapter using the example of an element of the intralogistics process.

4 The concept of a digital twin based on DES technology - results and discussion

In order to present the possibilities of using a digital twin in intralogistics processes, an example of using a digital twin using a DES simulator for the analysis and optimization of the operation of autonomous AMR vehicles was presented. Enterprise Dynamics software was proposed as a DES tool. This program can communicate (read and write) with any type of database. It is equipped with a set of lightweight database drivers that provide fast access to SQL database servers [19].

Omron has a built-in Advanced Robotics Command Language (ARCL) that enables the integration of a fleet of autonomous mobile robots (AMR) with an external system (automation, databases) and Integration Toolkit (ITK) an interface application that enables integration between the Fleet Manager system and the end-user client application, Manufacturing Execution System (MES), Enterprise Resource Planning (ERP), Warehouse Management System (WMS). In the case of the proposed concept, the ITK layer functionality is helpful, facilitating autonomous control of the AMR fleet using standard communication methods. The ITK layer enables real-time tracking of AMR data. For this purpose, it uses communication channels such as: RESTful Web Services, SQL with a PostgreSQL database, RabbitMQ [20].

The communication schema between the digital twin and the AMR vehicle is shown in Figure 3.

Figure 3 Communication schema between DT and AMR vehicle

Figure 4 shows a physical object - an AMR vehicle and its digital equivalent modeled in the ED software.

Figure 4 Physical object and its digital twin

To properly design a digital equivalent of an autonomous AMR vehicle, information about its parameters is necessary. The software allows the vehicle to be specified by defining its input parameters. Some of these parameters can be updated continuously thanks to the use of a digital twin. A set of such parameters is presented in Table 1.

Table 1 Matrix of length

Parameter	Description
Speed (m/s)	Maximum AMR speed
Acceleration (m/s²)	AMR Acceleration
Deceleration (m/s²)	AMR deceleration
Include deceleration	Slowing down at each turn according to the maximum permitted speed rule (m/s).
Min. angle (°)	Minimum turn angle for the maximum permitted speed (m/s) to be used.
Max. allowed speed (m/s)	Maximum allowed speed AMR
Load Time	Time required to load the goods
UnLoad Time	Time required to unload the goods
Load quantity	The amount of goods transported by a vehicle at one time
Battery capacity (Ah)	AMR vehicle battery capacity
Accl. Consumption (Ah)	Battery consumption for AMR acceleration
Decl. Consumption (Ah)	Battery consumption for AMR deceleration
Drive Consumption (Ah)	Battery consumption while driving AMR
Min. Capacity (%)	Minimum allowable capacity. If the battery capacity drops below this value, the AMR ends its task and goes to the Battery Charging Station for recharging.

Creating a digital equivalent and conducting simulation studies on it allows for the analysis of the intralogistics process and making appropriate decisions regarding the physical system. Enterprise Dynamics software provides two-way communication, therefore the output parameters resulting from the simulation experiments can be saved in an external database and become useful for the physical system.

Atom :	AMR						
		Average	St.Deviatior	LB (95%)	UB (95%)	Minimum	Maximum
Average task duration		28.07	0.11	27.10	29.04	28.00	28.15
Number of completed tasks		4213.50	27.58	3965.73	4461.27	4194.00	4233.00
Status Idle		0.10	0.01	0.05	0.15	0.10	0.11
Status Down		0.28	0.00	0.26	0.30	0.28	0.28
Status TravelFull		0.23	0.00	0.22	0.23	0.22	0.23
Status TravelEmpty		0.30	0.00	0.28	0.31	0.29	0.30
Status Load		0.05	0.00	0.05	0.05	0.05	0.05
Status Unload		0.05	0.00	0.05	0.05	0.05	0.05

Figure 5 Example set of output parameters for a digital AMR vehicle

Figure 5 shows an example set of output parameters for the digital AMR recorded during the simulation of its operation.

The use of a discrete event simulator to create a virtual model of the analyzed environment is known and presented by many authors [8-11]. Virtual models of intralogistic systems are created during the design of a physical system. However, many researchers note that relying solely on historical data as a reference for the analysis of various scenarios of the functioning of the intralogistic system obtained using the DES model is insufficient. Therefore, work is being carried out on the possibility of using DES in real time [14,16,17]. In such a case, the simulator should be fed with real-time data, which will increase the compliance of the Digital Twin with the real object. Therefore, the first stage is to master and improve the methods of communication between DT and the real object [1,17]. The proposed concept of using the DES simulator as an integral part of the Digital Twin concerns the area of intralogistics currently based mainly on autonomous systems. Therefore, the use of the proposed concept will provide support and effective decision-making in the analyzed systems. The virtual representation of the intralogistic system and two-way interaction in real time with the real world will certainly contribute to the conscious and timely management of the intralogistic system.

5 Conclusions

The article presents the concept of using a discrete event simulator as an integral part of a digital twin. The presented concept confirms the possibility of using DES technology as one of the main elements of a digital twin. The transition from the stage of a digital model, which is DES using historical data from a physical system, to a digital twin model requires a number of activities aimed at integrating discrete event simulators with many data sources in the analyzed process. In the case of intralogistics systems, in addition to information on parameters characterizing and influencing the operation of the means of transport involved in the functioning of the process, other information is also needed. These include, among others, the length of transport routes, places of picking up and putting down the load. Ensuring proper communication and data exchange between the virtual and physical models requires a direct connection with IoT sensors, servers or PLC controllers to ensure real-time communication. The presented possibilities of using DES as an integral part of a digital twin are subject to tests performed on a single element of the system, which is an AMR vehicle, in order to confirm the technical possibilities of using such a solution.

The presented work is the first stage of the planned research. The analysis of available technologies and the developed concept confirm the possibility of using DES as an integral part of the Digital Twin. In order to further develop research in this direction, it is necessary to carry out a real implementation of DES in DT. During real research, challenges resulting from the complexity of the proposed solution will certainly appear. The authors plan to test the proposed solution on an example intralogistics process.

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Review process
Single-blind peer review process.

https://doi.org/10.22306/atec.v11i2.280 Received: 23 Apr. 2025; Revised: 14 May 2025; Accepted: 02 June 2025

Study of tyres sustainability in the specific field of industry

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Keywords: sustainability, waste tyres, circularity, industry.
Abstract: Tyre sustainability is an important aspect of environmental responsibility in the automotive industry. This paper encompasses the processes of tyre production, use, wear and disposal in a way that minimizes negative impacts on the environment and human health. It focuses on extending the life of tyres, reducing their ecological footprint and recycling them efficiently. From production to use to recycling, a number of measures can be taken to reduce the negative impacts of tyres on ecosystems and society. These steps include innovations in materials, improved recycling technologies and a responsible approach to waste management.

1 Introduction

With the development of the automotive industry, tyres have become an integral part of everyday life [1]. We use them almost every day, whether when driving a car or riding a public transport bus, they are also widely used in air transport, but they are also an important link in freight traffic [2]. As a result of the development of society in the world, the demand for tyres is increasing, and the production of waste tyres is proportionally related to this [3].

The tyre manufacturing process can be divided into the following parts [2].:

- Material acquisition,
- Compound production,
- Production of individual tyre components,
- Tyre assembly,
- Vulcanization,
- Production quality control,
- Storage and delivery to sales.

Waste tyres represent a global problem and an increasing risk to the environment, because they are not biodegradable, are often improperly stored and disposed of. These stocks pose a threat of uncontrolled fires and other environmental risks. It is estimated that almost 1000 million tyres end of life each year and more than 50% are discarded without any further use [4]. Recycling and recovery of waste tyres are therefore being studied in many countries [5]. This step has necessitated a rethinking of the view and approach to waste in order to increase its recovery and drastically reduce the amount that needs to be disposed of or stored [3].

2 State of the art of the problematic

The basic components of any tyre are rubber, synthetic rubber, various fillers (such as silica or silicon dioxide) (Figure 1), and reinforcing and hardening agents [4]. Oil, resins, and other chemicals are used as plasticizers to improve the elasticity of the tyres [5]. The total number of components is over 200, and each has its own role in ensuring optimal tyre properties, such as fuel economy, performance, environmental protection, and safety. However, each manufacturer carefully protects the exact composition and ratio of the individual components contained in the tyres [3].

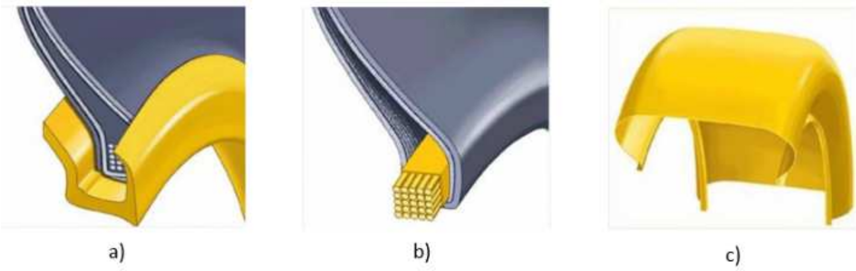

Figure 1 a) heel b) heel cord c) rubber layer [4]

The sidewall (Figure 2) is an essential part of every tyre. There are no steel reinforcements in the sidewalls, because the role of the sidewall is to resist external influences, bending and vibrations [3]. They are mainly made of natural rubber. In practice, when driving on the track, it is the sidewall that keeps the tyres “in place”, since when cornering at high speeds, under the influence of the laws of physics, it looks like the rim is pushed inward and the tyre is pushed outward from the car [3]. To the naked eye, in slow motion footage, it looks as if the tyre is jumping in and out. In these situations, it is the flexibility of the sidewalls that ensures the proper functioning of the tyre [2]. The largest part of the tyre is made up of the carcass otherwise called the radial cord layer, and the composition of this layer determines the basic properties of the casing [4]. It is a high-strength fabric, composed of aramid fibers, polyamide, polyester, viscose and other materials. Depending on the composition of the cord layer, tyres are divided into diagonal and radial, depending on the direction in which the cord layers are laid [5].

Figure 2 a) sidewall b) carcass[4]

The composition of different types of tyres is not identical. Each type is designed for different conditions and must therefore meet different, specific requirements (Figure 3). The proportion of individual components in the tyre and their production itself depends mainly on the vehicle and terrain the tyres are intended for [6]. Important production parameters are, for example, the type of vehicle and its weight, tyre dimensions and speed index.

Figure 3 a) bumper b) tread [4]

The construction of the finished tyre is the most demanding part of the entire manufacturing process. The other components are inserted into the construction machine and the finished tyre is created. Its inner diameter is formed by a steel, or bead, cord, which is covered by an inner rubber layer that replaces the tyre’s inner tube. The inside of the tyre and the sidewall are separated by a tread. The tread is made of steel cords and natural rubber (Figure 4). The steel cords absorb road irregularities. If the sidewall is cut, the tyre becomes unusable and cannot be repaired.

Figure 4 Flat Spot [4]

3 Work methodology

The selection of tyres is carried out according to two basic criteria: the characteristics of the circuit and environmental impacts [7].

First of all, the individual appearance of the track is assessed, how many fast corners, slow corners, straights it has [8]. In slow corners, i.e. those that make sharper angles, the pressure on the tyre is less and therefore overheating occurs later. In this case, it is better to choose softer tyre compounds [9]. In fast corners, the car has more downforce and the force that acts on the car is transferred to the tyre in the form of lateral force. These quantities are directly proportional, i.e. the higher the speed, the higher the downforce and the greater the force acting on the tyres and therefore it is better to choose harder tyre compounds [10]. If the track has long straights or more short straights, the tyres have room to cool down, softer compounds are suitable, otherwise, if there are few straights, harder compounds are preferred [11]. The second step to consider when choosing tyres is the track surface. We know two basic criteria for track surfaces: macro roughness and micro roughness. To understand, it is important to imagine the composition of asphalt itself. Bitumen is a mixture of hydrocarbons that have been extracted with organic solvents from sediments containing organic matter. Similar hydrocarbons are also found in gasoline, tar, oil, and plastics [9]. Bitumen is a substance with a thick, sticky liquid consistency like syrup that solidifies at normal temperatures. It is mixed with aggregate, which forms gravel and stones. When looking at the track, this mixture is visible to the naked eye [11].

4 Results and discussion

After the new asphalt is laid, the surface is not perfectly laid and compacted for several years and the aggregate, which contains stones, causes the surface to be rough (Figure 5). Macro roughness makes the track more grippy and the car has more grip, but it is very aggressive towards the tyres [12]. This raw asphalt guarantees the selection of harder tyre compounds. In addition to the aggregate, there is a second problem caused by the new asphalt [13].

Figure 5 Asphalt [1]

The oils found in bitumen are sensitive to temperature changes and at higher temperatures they separate from the compound and coat the track surface [10]. This in turn causes less grip and the risk of the tyres slipping on the track [4]. After a few years, depending on use, the aggregate slowly compacts and the surface becomes smoother. This process is closely monitored and when comparing the compounds used on one circuit, we see different compounds over the years [7]. Micro roughness is the texture of the surface itself. It assesses the connection and relationship between the rubber on the surface of the tyre and the road surface [9]. It looks at this problem from a chemical point of view so that the molecules in the tyres and the molecules in the asphalt have the best possible grip. Another major factor influencing tyre choice is environmental factors. The temperature of the road has a significant impact on tyre choice. In many cases, a colder track is flatter and more conducive to energy distribution in the tyres during corners [12].

The higher temperatures can cause the bitumen in the asphalt to deform and release oils, which will cause the tyres to have less grip [11]. Of course, Pirelli doesn't know in advance what the weather and temperatures will be during the race weekend, so they will be given a clue as to what the climate is in the country [13]. If the country has alternating periods of rain and dry weather, this will keep the track cold and wash away the rubber. So tracks without a rubber layer will be better suited to harder compounds, but only if it's not too cold [14].

Conclusion

Tyre sustainability focuses on minimizing their negative impact on the environment throughout their entire life cycle, from production, through use, to recycling and disposal. This issue is important because tyres are made from materials that can have harmful effects on nature if not properly processed. From the research carried out, it is important to focus on:

- the development of tyres with a longer lifespan and lower maintenance requirements. These technologies can reduce waste and improve overall sustainability.
- the production of smart tyres, which include technologies that monitor tyre wear and pressure, which allows for better management of their lifespan and reduce inefficient use.
- the proper recycling of waste tyres so that technological systems are designed to minimize the environmental impact of tyres on the environment.

In conclusion, supporting the circular economy of tyres is the process of recycling and reusing tyres with the aim of minimizing waste and maximizing sustainability.

Acknowledgements
This work was supported by the project VEGA 1/0210/25 and KEGA 014TUKE-4/2025 granted by the Ministry of Education, Research, Development and Youth of the Slovak Republic.

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Review process

Single-blind peer review process.

https://doi.org/10.22306/atec.v11i2.283 Received: 23 Apr. 2025; Revised: 13 May 2025; Accepted: 05 June 2025

Prototype design of an inverted pendulum two-wheel vehicle

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Keywords: two-wheeled, self-balancing vehicle, prototype, wireless.
Abstract: This study presents the design and implementation of a two-wheeled self-balancing vehicle based on the inverted pendulum principle, controlled wirelessly via a PC interface. The system integrates an ATmega-based embedded platform with MRF24J40MA wireless transceiver modules for real-time bidirectional communication between the vehicle and a host computer. The vehicle's structure includes a custom mechanical frame, sensor modules (including accelerometers and encoders), motor drivers, and an LCD interface for status display. Control algorithms, including PID tuning, are executed through a PC-based graphical interface, allowing precise adjustments and live monitoring. A dual-microcontroller configuration—ATmega8 for PC interface and ATmega32 for onboard control—facilitates modularity and reliable data handling. The results confirm the system's effectiveness in maintaining balance and responding to commands under various test conditions. This prototype serves as a foundational model for further exploration in autonomous robotics, wireless control systems, and real-time embedded applications.

1 Introduction

Wireless data transmission is a large area in information electronics, the transmitted data can be analogue or digital [1-5]. In wireless data transmission, the most effective is still transmission by electromagnetic waves or radio waves, because of the advantages of long-distance transmission, multi-directional, high operating frequency. The article aims to build a simple system consisting of an intermediate board that performs data forwarding between the computer and the RF transceiver module, another RF transceiver module mounted directly on the self-balancing two-wheeled vehicle with the task of sending control commands to the robot and collecting data that needs to be processed and sending it back to the computer. To solve this problem, the research takes advantage of the microcontroller's ability [6-10] to transmit and receive serial data thanks to the UART in the chip. The microcontroller has the ability to perform multi-processing communication, which is very suitable for data transmission in a wireless network system consisting of many processors. Wireless technology is applied to create compact, smart, flexible robot models on all terrains. By adding a remote observation camera, people can control them as desired, creating the desired work efficiency.

A self-balancing two-wheeled vehicle is a robot that can balance itself in a vertical position with only two coaxial wheels [11-15]. The balancing process is performed by the controller [16-19]. The two wheels will move forward or backward to always maintain the vertical state of the vehicle so that it does not fall. The two-wheeled vehicle is also capable of moving on different terrains like other means of transport. The content of the article is divided into 3 parts. The first part is responsible for studying the theoretical basis. The second part is to study the hardware features, and the last part is to design the control software, hardware circuits and the results achieved. This research not only demonstrates the feasibility of wireless control in dynamic robotic systems but also highlights the synergy between embedded microcontroller platforms and RF communication modules. The proposed design offers a practical and scalable solution for developing intelligent mobile robots. Ultimately, the study provides a comprehensive approach to designing and implementing a self-balancing two-wheeled vehicle, from theoretical modelling to hardware integration and control software development.

2 Hardware and software design

The MRF-AVR-PC communication circuit schematic diagram is shown in Figure 1. The circuit is a complete embedded wireless communication system built around the ATmega8L microcontroller and the MRF24J40MA wireless transceiver module. At the heart of the system, the ATmega8L handles core processing and communication tasks. It operates using a stable clock signal provided by an external crystal oscillator, connected via two capacitors to form a classic crystal-based timing circuit. To ensure proper operation and maintain clean reset conditions, a reset circuit is included, consisting of a push-button and passive component that allow manual system reinitialization.

Power is supplied to both the microcontroller and the wireless module through dedicated voltage regulators. The ATmega8L typically operates at 5V, while the MRF24J40MA module requires a regulated 3.3V supply. Each power line is stabilized using filtering capacitors to reduce voltage ripples and electrical noise. The ATmega8L communicates with the MRF24J40MA using the SPI protocol, employing pins for data in (MOSI), data out (MISO), clock (SCK), and chip select (CS). Additional control lines such as RESET, INT, and WAKE are used to manage the wireless module's operational states and event handling. To enable communication with a personal computer, the system integrates a MAX232 IC, which converts TTL logic levels from the microcontroller to RS-232 voltage levels compatible with a standard DB9 serial port. This allows for seamless UART communication between the microcontroller and external software on the PC. The MAX232 utilizes external capacitors as part of its internal charge pump to generate necessary voltage swings for RS-232 signalling.

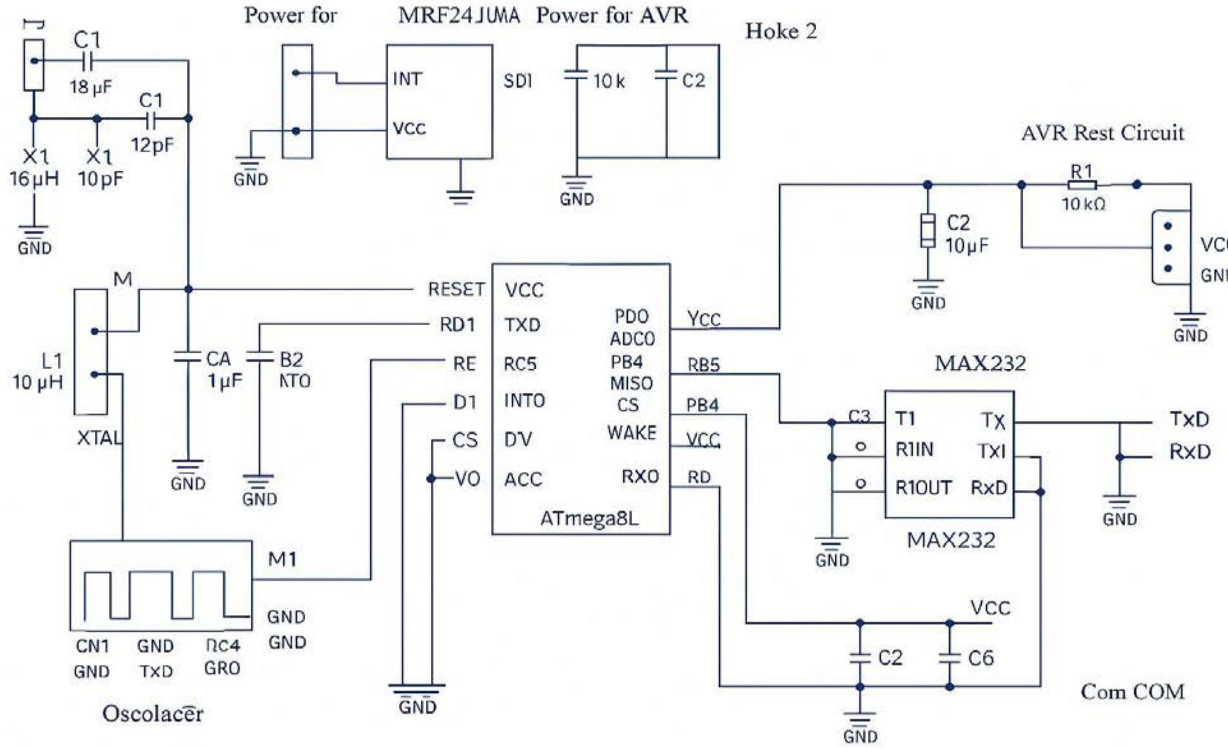

Figure 1 MRF – AVR - PC communication circuit schematic diagram

For development and firmware updates, an in-circuit serial programming (ICSP) header is provided. This interface allows programmers to upload or modify the ATmega8L firmware without removing the chip from the board. Overall, the design supports wireless data exchange between the PC and remote devices using ZigBee protocol, while ensuring stable operation, programmable control, and robust communication through well-integrated analog and digital subsystems.

Figure 2 represents a complete embedded system for a robot control unit, designed around the ATmega32 microcontroller. The system integrates multiple functional modules to support sensor input, motor control, wireless communication, user interface, and system monitoring.

At the core of the circuit is the ATmega32, a versatile 8-bit AVR microcontroller that interfaces with several peripheral devices. A 16 MHz crystal oscillator and two capacitors ensure stable clock operation for precise timing and execution. The microcontroller receives regulated power through two voltage regulators: the LM1117 (3.3V output) and the 7805 (5V output), each stabilized by decoupling capacitors to reduce voltage noise and fluctuations. A manual reset circuit with a tactile switch and pull-up resistor is included for system reinitialization.

Sensor input is handled by an MMA accelerometer module, connected to the ATmega32 through I2C or SPI pins, depending on configuration. A motor encoder module is connected to digital I/O pins to track motor position and speed, feeding essential feedback to the control algorithm. The MOTOR block indicates output connections to a motor driver circuit, allowing the microcontroller to control motor rotation based on commands or sensor feedback.

For wireless control, the system includes an MRF24J40MA ZigBee module, which communicates with the ATmega32 via SPI and is powered through the 3.3V regulator. The control signals from this RF module enable the robot to receive commands remotely. An ISP (In-System Programming) header is provided to upload firmware directly to the microcontroller, making it easier to update the software without removing the chip.

User interaction and system status are facilitated through a 16x2 LCD module connected to the microcontroller's PORTC. This display outputs relevant data like sensor readings or mode indicators. Additionally, an LED with a current-limiting resistor (R3) serves as a simple status indicator. A push button (SW1) allows user input, such as mode switching or command triggering.

Overall, the system combines multiple subsystems—including motion sensing, wireless communication, motor control, display, and user input—into a single cohesive unit. It is ideal for mobile robot applications, remote sensing platforms, or any embedded control system requiring real-time feedback and user interaction.

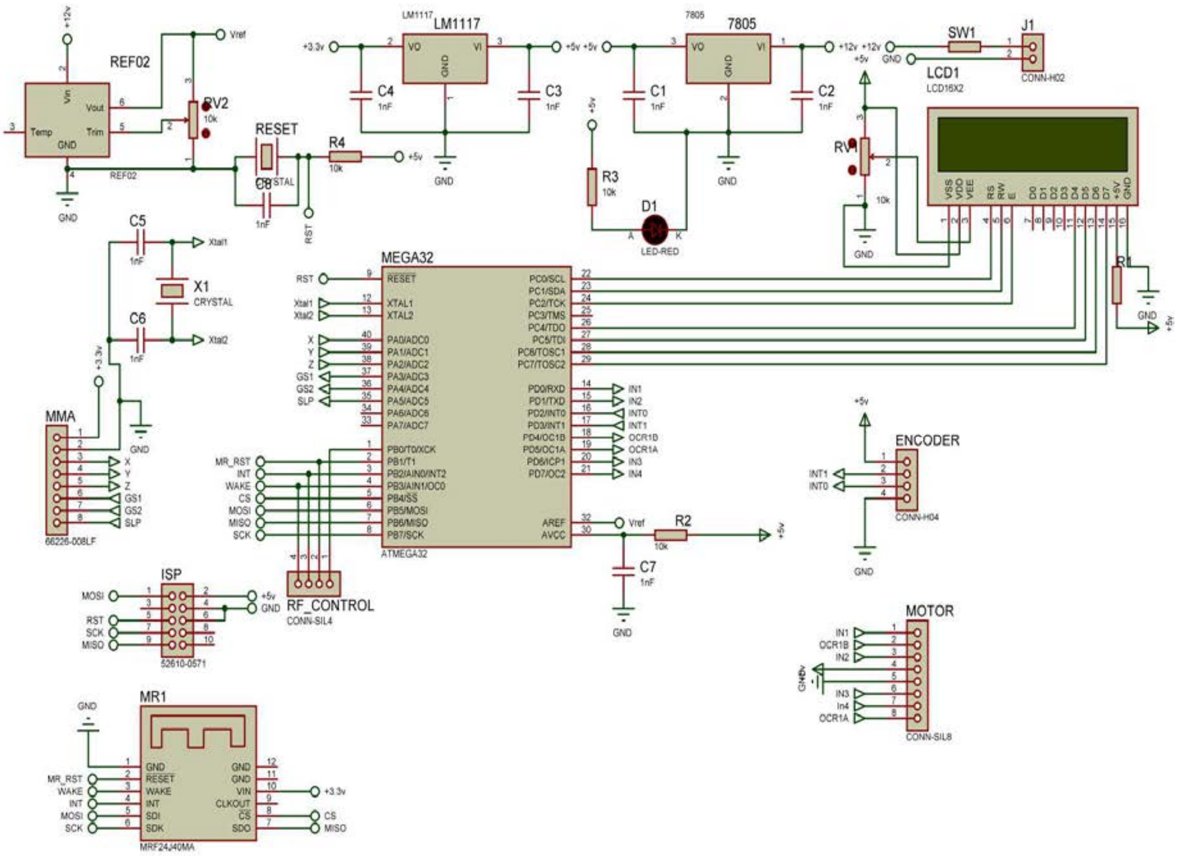

Figure 2 Robot control circuit schematic diagram

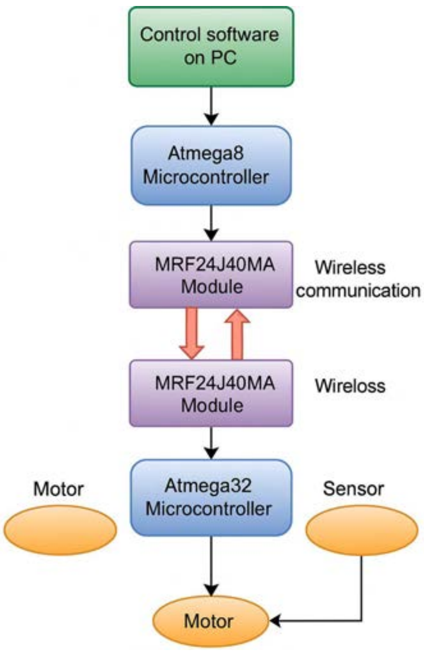

Figure 3 Block diagram of system

The block diagram of system as shown in the Figure 3. The system begins with the PC-based control software, which sends commands to the Atmega8 microcontroller. This microcontroller communicates wirelessly via a MRF24J40MA module. The signal is received by another MRF24J40MA module, which forwards the data to the Atmega32 microcontroller. The Atmega32 processes the data, reads information from the sensors, and drives the motors accordingly. This forms a wireless closed-loop control system between the PC and the robot.

The Figure 4 shows a graphical user interface (GUI) for a program titled "Program for Controlling a Self-Balancing Two-Wheeled Vehicle." The layout is visually divided into several functional sections designed to facilitate communication, control, and monitoring of the vehicle. On the left side, the "Communication Control" section allows the user to select a COM port and baud rate (e.g., COM1 and 2400) to establish a connection with the vehicle via a wireless module like the MRF24J40. Below this is the "Motor Control (PID)" section, where the user can input PID (Proportional, Integral, Derivative) values for tuning the vehicle's balancing response. Buttons for confirming or cancelling the settings are also provided.

The control software on the computer is designed as follows:

Figure 4 Control program interface

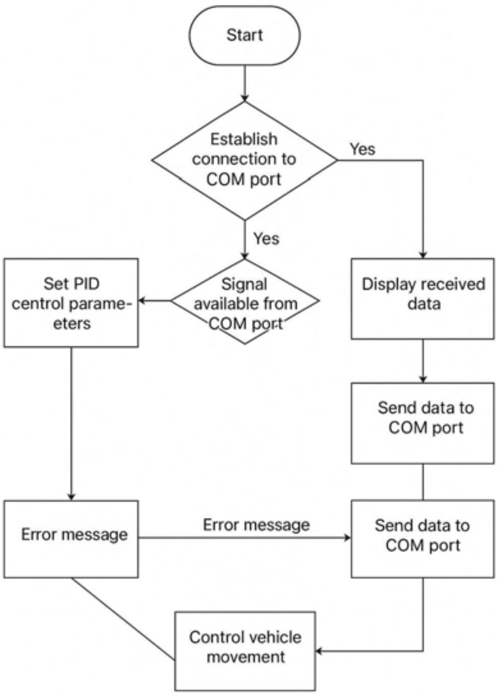

Figure 5 Algorithm flow chart of the control program on PC

Figure 5 presents a flowchart that outlines the operational logic of a program used to control a system—likely a self-balancing vehicle—through a COM port communication interface. The process begins with establishing a connection to the COM port. Once connected, the program checks for signal availability from the port. If a signal is detected, it allows two parallel operations: displaying the received data and plotting the vehicle's status on a graph, indicating real-time feedback from the vehicle's sensors.

Concurrently, the program also proceeds to set PID (Proportional, Integral, Derivative) parameters for the motor. If the parameters are set correctly, data is transmitted to the vehicle through the COM port. If an error occurs during the PID configuration, the system generates an error message. Additionally, if there is no issue, the program continues to control the vehicle’s movement based on the received instructions. Overall, the flowchart illustrates a well-organized structure for managing serial communication, motor tuning, real-time monitoring, and error handling, essential for ensuring responsive and stable control of a self-balancing robotic system.

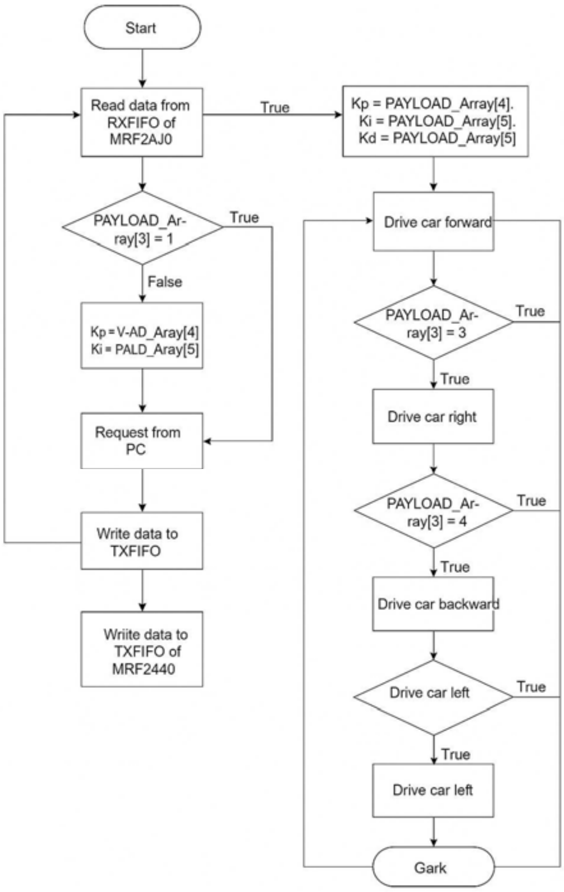

Figure 6 Algorithm flow chart of remote control of two-wheeled vehicle

Figure 6 displays a structured flowchart representing a control algorithm for a car system that communicates with a PC via a wireless transceiver module (MRF24J40). The process begins at the "Start" block and immediately proceeds to read incoming data from the RXFIFO register of the MRF24J40. If data is successfully read, the system evaluates specific control conditions based on the content of PAYLOAD_Array [3].

If PAYLOAD_Array [3] equals 1, the program assigns values to the PID parameters Kp, Ki, and Kd using elements from the payload array. Subsequent decisions branch based on whether the array's index equals 2, 3, 4, or 5, which trigger respective motion commands: driving the car forward, right, backward, and finally, left. Each condition leads to an action box indicating a directional command to the vehicle.

If the data read condition is false or no relevant control condition is met, the flow proceeds to check if there is a data request from the PC. If true, the necessary data is written into the TXFIFO buffer and transmitted back via the MRF24J40 module. The flowchart uses standard symbols with decision diamonds and process rectangles and includes corrected English for logic terms like “True” and “False,” ensuring clarity. However, a minor typo is present in the terminal block labelled "Gark" instead of "End" or "Finish," and that could be revised for improved accuracy.

3 Result and discussion

The Figure 7 shows a custom-built communication circuit board, likely used for serial data transmission in embedded systems. At the center of the board is a dual in-line package (DIP) microcontroller, which serves as the main processing unit. To its left, a red module labeled “MRF24J40MA” is mounted, which is a 2.4GHz IEEE 802.15.4 wireless transceiver, commonly used for ZigBee-based communication. On the right side, there's a DB9 serial connector, indicating that the board supports RS232 communication, allowing it to interface with PCs or other serial devices.

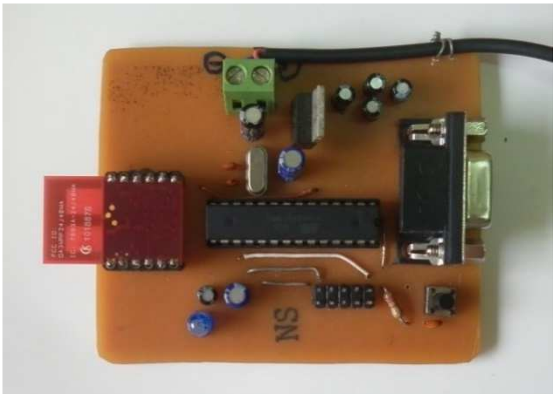

Figure 7 MRF24J40MA communication module to connect to computer

The top part features a green terminal block for power supply or other external connections, along with various supporting electronic components such as capacitors, resistors, a crystal oscillator (for clock signal generation), and voltage regulators.

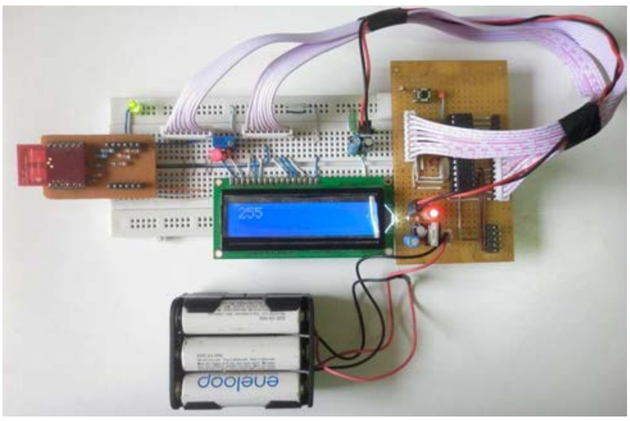

Figure 8 MRF24J40 Board to test wireless transmission between two MRF24J40 modules

The Figure 8 shows a test setup for a microcontroller-based wireless communication system. On the left, the red wireless module (MRF24J40MA) is connected to a small custom PCB, which is mounted on a white breadboard. This module handles IEEE 802.15.4 communication, often used in ZigBee applications. The breadboard also includes supporting electronic components such as LEDs, resistors, and a 16x2 character LCD display that is currently showing the value “255,” suggesting it is displaying data received wirelessly or processed by the microcontroller. A custom-designed main control board is visible to the right, connected via a ribbon cable. This board likely contains a microcontroller and associated circuitry for managing communication and data processing. Power is supplied from a battery pack at the bottom, containing two AA Eneloop rechargeable batteries.

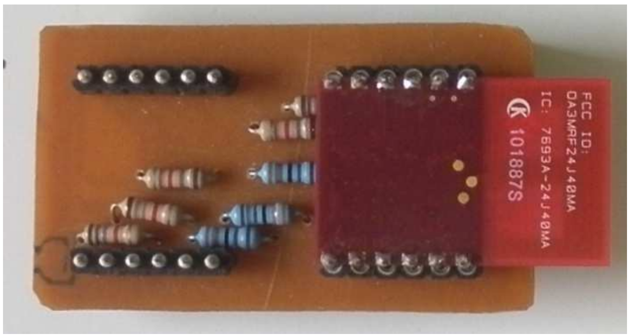

Figure 9 MRF24J40MA module mounted on self-balancing two-wheeled vehicle

The Figure 9 shows a custom-made adapter board for a wireless communication module, specifically the MRF24J40MA, which is a 2.4GHz IEEE 802.15.4/ZigBee transceiver manufactured by Microchip. The red module is securely soldered onto a brown single-layer PCB, and multiple through-hole resistors are mounted to condition or protect the data lines connected to the module. Two rows of pin headers are used for interfacing this board with other microcontroller systems, such as development boards or test circuits, via jumper wires or ribbon cables. The resistors likely function as pull-up, pull-down, or current-limiting resistors to ensure reliable data transmission and electrical compatibility.

The Figure 10 displays a prototype of a two-wheeled self-balancing robot, designed to operate based on the principles of an inverted pendulum. The structure is primarily composed of a metal frame with two wheels at the base, allowing mobility and dynamic stabilization. Mounted vertically on the frame is a tall support beam, which likely serves as the main axis for balance control. Near the middle of the frame is an electronics section, consisting of several custom-built circuit boards and an LCD screen, indicating real-time feedback or sensor readings such as angle, speed, or control output. At the top of the robot, a battery pack consisting of multiple cylindrical cells is securely attached to power the system. Numerous wires connect the sensors, actuators, and controllers, showing a test or development phase. This setup is commonly used in research or educational projects to study real-time control systems, especially PID or fuzzy logic controllers, applied to robotics and mechatronics. The robot is likely intended to demonstrate wireless communication, autonomous balancing, and mobility in embedded systems.

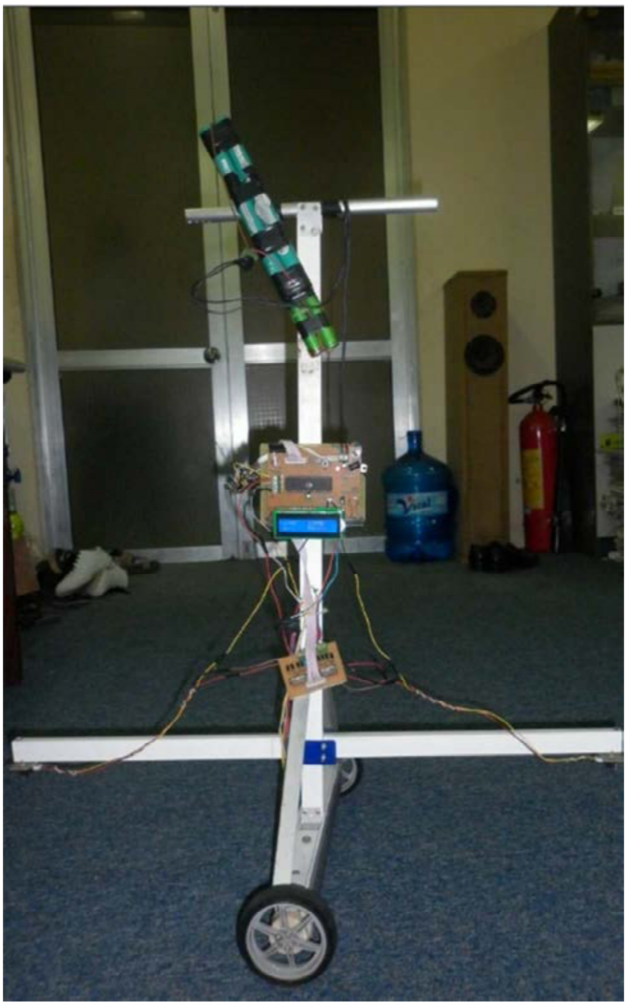

Figure 10 Self-balancing two-wheeler prototype

The experimental evaluation of the self-balancing two-wheeled vehicle prototype yielded positive results, validating both the hardware integration and the wireless control strategy. The wireless communication system, using the MRF24J40MA transceiver modules, demonstrated reliable and stable data transmission between the PC and the vehicle in real-time. The communication board (Figure 7) and wireless test setup (Figure 8) confirmed that the modules could maintain continuous two-way communication with minimal data loss within the operational range tested.

In terms of system performance, the embedded control unit, composed of the ATmega8 and ATmega32 microcontrollers, effectively processed sensor inputs and executed the PID control algorithms, enabling the robot to maintain balance even under slight external disturbances. The practical deployment of the communication system onto the vehicle (Figure 9) illustrated that the compact integration of the wireless module did not interfere with the dynamic stabilization of the system.

The full vehicle prototype (Figure 10) successfully demonstrated the inverted pendulum control principle. Throughout testing, the robot maintained an upright position and responded accurately to directional commands (forward, backward, left, right) issued via the PC interface. The LCD feedback system allowed real-time monitoring of system parameters, improving user interaction and facilitating fine-tuning of the PID control parameters.

However, minor limitations were observed during testing. The vehicle's response time showed slight latency under longer-range wireless transmission, primarily due to the lower baud rate (2400 bps) used to enhance stability. Moreover, while the current control algorithm handled moderate disturbances well, performance degradation was noticeable under aggressive tilting or rough terrain, suggesting a need for enhanced control strategies, such as adaptive PID control or implementation of a Kalman filter for sensor fusion.

Overall, the results affirm that the designed system meets the intended objectives: demonstrating wireless real-time control of a self-balancing two-wheeled vehicle, validating modular embedded design, and offering a platform for further research in advanced control algorithms and wireless robotic systems.

4 Conclusion

The research successfully demonstrates the development of a self-balancing two-wheeled vehicle based on the inverted pendulum principle, integrating both hardware and software components with wireless communication capabilities. By employing the MRF24J40MA module in conjunction with AVR microcontrollers, the system enables real-time data transmission and remote control via a PC interface. The control software allows users to input PID parameters and monitor the vehicle’s state dynamically, creating a responsive and adaptable platform for balance and motion control. Hardware subsystems, including motion sensors, motor drivers, and an LCD interface, were effectively integrated into a compact and functional design. Experimental validation through various test setups confirmed the system’s ability to maintain balance and respond accurately to remote commands. This prototype offers a valuable foundation for further development in wireless robotic control systems, educational tools for control theory, and advanced mobility research. Future enhancements may focus on refining the algorithm, improving energy efficiency, and expanding autonomy for more complex real-world applications.

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Review process
Single-blind peer review process.

https://doi.org/10.22306/atec.v11i2.286 *Received: 07 May 2025; Revised: 14 June 2025; Accepted: 25 June 2025*

Managing technological innovation: organizational and administrative strategies for digital marketing

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Keywords: technological innovations, strategy, management, marketing.

Abstract: This article is written on the technological innovation governance as part of the organizational and managerial strategies for digital marketing. The objective of the research is to identify the most important issues in the process of implementing innovations in the company and to propose efficient methods for controlling technological operations and changes. The article addresses the following challenges: the difficulty of implanting new technologies in the old structure of the organization, resistance to changes at the personnel level, the priority of ensuring the integration of innovations in the strategic development of the company. Attention is also drawn to the necessity of best investment for implementation of creative solutions, and to the requirement of any time technology market changes. Solutions to the problem include establishing adaptive strategic management programs to new technologies, creating innovative cultures in institutions, and training workers in the change readiness development of workers. Also, the implementation of digital platforms and tools to track and manage the innovation processes plays a key role. The method of investigation comprises data analysis methods, econometric models or mathematical formulas in order to study the effect of technological innovations upon organizational activities and the effectiveness of the latter. The novelty of this work is represented by the system approach toward innovation management development that based on the combination of various management and organizational methods. The key findings of the paper clarified agree that for any well-established technologies strategy should be dependent on flexibility, employee training and the cultivation of an innovating setting.

1 Introduction

Managing technological innovation is a key element of successful functioning of organizations in the context of rapid technological progress and globalization. In recent decades, technological innovations have covered all areas of human activity: from production and transportation to finance and medicine. However, despite the obvious benefits that can be achieved through the implementation of innovative solutions, many companies face a number of difficulties in integrating technologies into their business processes. In such conditions, the need to develop and implement effective organizational and management strategies becomes especially relevant. Technological innovations have a unique ability to radically change both internal processes in companies and their interaction with the external environment. However, the successful implementation of these technologies requires not only the availability of innovative solutions, but also an appropriate approach to their integration into the corporate culture and strategy of the organization. Many companies at various stages of their digital transformation face difficulties associated with change management, inefficiency of internal processes, as well as insufficient personnel qualifications to work with new technologies [1]. This indicates the importance of developing effective organizational and management strategies aimed at the successful implementation of technological innovations.

The relevance of the study of technological innovation management is associated with two main factors. Firstly, rapid changes in technology require organizations to be able to quickly adapt to new conditions and implement innovations, which becomes the key to their competitiveness. Secondly, the implementation of innovations should be an effectively managed process, including strategic planning, resource management, personnel training and adaptation of organizational culture. This requires the development of comprehensive approaches and strategies that will ensure synergy between new technologies and existing business processes. One of the key aspects of innovation management is the need to balance risks and opportunities. Technological innovations are often associated with high initial costs, as well as risks such as unsuccessful technology integration, unpredictable changes in the market or even employee resistance. Despite this, successful implementation of innovative solutions can significantly increase the efficiency of production processes, reduce costs and improve customer service, which makes them extremely important for any organization seeking to maintain or improve its market position.

1.1 The need for research and unsolved problems of managing technological innovations in modern conditions

The need for research in the field of technological innovation management for digital marketing is confirmed by the lack of universal models or approaches that guarantee successful implementation of innovations. In practice, companies often face a number of unresolved problems that hinder the implementation of innovative solutions. These include:

- Resistance to change. The implementation of new technologies often meets resistance from employees who are not ready to adapt to new working conditions. This may be due to both the lack of necessary skills and the psychological perception of change. As a result, organizations cannot effectively use the potential of technologies.
- Absence of strategic clarity. Organizations quite frequently adopt new technologies without sufficient knowledge of how they must be linked to the established organizational architecture. Reactive decision-making If you don't have a long-term integration plan, you'll use the latest technology for the wrong problem.
- Lack of skilled man power. New tech requires specialists to make it work, the adoption of new equipment and techniques for example. But in the labour market, such personnel are not enough - processes of adapting and integrating technologies are blocked for their lack.
- Uncertainty in estimations about the innovations. In the world of business, many companies fail to measure the true impact of incorporating cutting-edge technology into its operation. That makes it harder for rulers or others to decide whether to scale an innovation up, or abandon it.
- High installation costs. It takes a lot of money and time to make technological innovation happen.

Therefore, in spite of the apparently serious significance and advantages of introducing technological innovations, the solution to the aforementioned issues is obviously one of the most important challenges faced by management researchers and practitioners [2]. Even though the premise of technological innovations is a sound one, this is only to the extent that technological innovations are managed effectively and in accordance with the firm's overarching strategy and managerial approaches.

The necessity of developing in this field is caused by the problem of the devotement of new more relevant technology management methods and implementation of technological novelties additional measures that take into account changes of the external environment and that contribute into minimizing risks and usage of the capabilities of new technologies as effective as possible. This is particularly relevant with rising digitalization and new technological trends – think artificial intelligence, blockchain and the Internet of Things, all of which are driving fundamental change within business processes.

Therefore, the research on technological innovation management in the context of organizational and management strategies is crucial to understand how organizations can adopt successfully new technologies in an era that sustainable grow and desire for competitiveness are the only way to achieve a long-lasting success in the market.

1.2 Theoretical foundation of the characteristics of technological innovation management on digital marketing strategies

In a fatly changing environment, technology innovation management becomes process for companies' strategic development. Innovations stimulate development and the improvement of business processes, and generate new competitive environments. Nevertheless, for technological change to be fully exploited, sound theoretical and practical approaches for managing innovation are critical. The theory of technology innovation management in post-modern corporations. Technology innovation is related to the development and application of new or substantially improved technology solutions that change business processes and products of a company [3]. These innovations can be product innovations and process innovations such as for example new forms of production, automation or digital technologies.

The theoretical framework of technical innovation management is the strategic goal on the systematic implementation of innovative solutions in the activities of an enterprise. Innovation management theory defines innovations as a significant factor of the long-term competitiveness of a corporation, and their management involves a number of stages, namely, the research and development of new technologies, their institutionalization, monitoring and modification in the course of use. Organisations may also apply a range of theoretical models in the process of directing and controlling innovation in order to maximise the efficiency and effectiveness of the way the technological development process is organized and managed. One of the most famous frameworks is the Open Innovation Model which mentions about idea generation from both within and outside the company rather than just from within, by partnering & collaborating with entities outside the organization such as universities, startups, other companies etc. This model allows companies to accelerate the speed at which groundbreaking products are developed and to save on research. Another significant approach is based on the technology synergy model asserting that innovation is successful when multiple technology solutions come to interact with one another, producing a new value. In such a scenario, a company should perceive 'technologies as an ecosystem rather than as isolated solutions.' Most important to our theoretical work in TIR is uncertainty, a central issue in the management of technological innovation. As with many other technologies, technology advance is unquestionably a high-risk undertaking – technological risk, financial risk, operational risk. Companies find it challenging to foresee the consequences of new technologies on their business. Moreover, it is not always the case that the new technologies need a lot of investments, but those who cannot afford it, that is, the small companies, do not expect to be able to buy the new technologies [4]. There's also the issue of resistance to change. It's not just employees who're unready to introduce new technologies into the workplace, either; it's the company's whole culture, designed to keep old, familiar ways of working central to the business. In these cases, innovation management consists in changing the corporate culture, training the staff and setting up incentives for the introduction of new performative innovations. If we refer back to the theory of the management of technological innovation, it becomes clear that implementation of innovations is a comprehensive process, which comprises strategic planning, organizational flexibility, responsible leadership, and support for employees. Knowing the mathematical assumptions is of a great assistance when it comes to companies not only minimizing risk, but also to make the best out of there venation of new technologies and competitiveness in growth. Given the accelerating pace of technological change, firms which successfully do so can not only survive but also prosper in the market.

2 Literature review

The meaning of the word “innovation” does not seem to be agreed upon in the scientific literature. While some authors consider inventions as a whole system, for other authors inventions are processes or outcomes. [5] defines innovation as "a systemic, contradictory, dynamic whole” while [6] consider it as “a systemic process to transform a novelty into business”. This variety of perspectives reflects the necessity to clarify and to standardize in the terminology that is used in the field of innovation management. Note that there are various typologies of innovation development strategies based on different principles. They fall into several dimensions, one of the most frequently used is classification on strategy according to its amount of reflection on society, intervention in the society’s welfare improvement and consciousness in the intervention [7]. But these suggested taxonomies are problematics, because of their too detailed complexity or the absence of pragmatic managing. This points in the direction of the importance of establishing more generalized and application-oriented models of SIM. In the contemporary context of research, much attention is paid to such directions as open innovation, external partners-cantered cooperation, digital technologies application, and flexibility of project management approaches [8]. The company can respond immediately to changes in the external context and to new external knowledge and resources.

Organizational structure and leadership are what an organization requires to work properly. There are numerous classification and construction approaches for them in the scientific literature, each with its own pros and cons. There are various activities and processes of Innovation Management that involves in generating ideas, products or services that is currently under process in today's organization. Key elements in this area are strategic planning, project management and coordination with different departments of the organization. In innovation management literature [9] that refers innovation, a source of sustainable growth and competitive advantage. On the other hand, contemporary studies also suggest that flexibility and adaptability are crucial since the technology market is in rapid shifting [10]. The theoretical concept of open innovation first emerged in the work of [11,12]. Open innovation holds that firms can and should make better use of external ideas and technologies in their own business. This implies that successful innovation management policies need to encompass the cooperation with other enterprises, universities, research centers. Studies like [13] point out that the interaction and sharing of knowledge is N Spingoid et al the force proper to enable the diffusing of innovations. An innovation management concept cannot survive without a model, which will help an organization to ensure that it uses its resources and competences in an effective way, producing new technologies. [14] state that firms can thrive by creating distinctive innovations which satisfy customer requests and create competitive edges. For this purpose, there are generally two major strategies in innovation strategy: differentiation and cost leadership.

Organizational structure design to manage innovation: The most crucial management innovation strategy According to [15], the best approach to manage innovation must be towards creation of an open organizational structure for learning what may be changed quickly to the demand of both external environment and internal entry of new technological innovation. [14] in the classical piece suggests that companies with more sophisticated or technology-oriented companies should have flexible and more informal structures in place to ensure an effective implementation of innovation projects. This view is supported by more recent studies, e.g., [15], which finds that flexible firms are better able to adopt innovations. The strategy of building the culture of innovation is also regarded to be the condition of the implementation of the technological innovations. [11] organizational culture would challenge and change to creativity, risk -taking and willingness to experiment. Studies prove that companies perceived as most innovative perform substantially better in developing new products and technologies. Good practices of innovation management in organizations also include establishing cross-functional relationships. This includes the interaction of the various "silos," such as R&D, marketing, and sales. The investigation reveals that this kind of close relationship with the customer is beneficial for enhanced consumer insight and to decrease the rate of time taken to respond to a change in technology (R&D) [16]. Project management for innovation calls for special risk and uncertainty-cantered methods. A critical tool in this domain is the Stage-Gate model introduced by [17]. This model breaks down the innovation process into a number of stages with gates at each and so lowers the risks of failure and makes better use of resources. In today's rapidly evolving technology and changing market, decision making is even harder. Two tools that research shows should be used for successful innovation management are a sensitivity analysis and a model. [16,17] stress the need for flexibility to adapt rapidly to uncertain situations. Contemporary research also highlights networking and strategic alliances as being critical in innovation management. [18] provides examples of successful companies that utilized such partnerships with third parties in order to speed up the time to market for innovations. Innovation management in this perspective innovation management IS the management of the firm's resources to adapt to environmental change, both the resources within the company and the resources outside the company with which the company cooperates. Some aspects of the subject are in depth explored in always prolific literature about the field of innovation management, but other concepts are so far not well delineated. First, a more thorough investigation is required to establish the conditions influencing the effect of the external environment on the innovation demonstration. It has been proved that government policies, economic instability and even social change, etc. play significant roles on the innovation strategies in practice and they are often ignored in the extant models [19]. Then, many studies are concerned with the performance of larger companies, while there are other issues that SMEs need to tackle, such as lack of resources or access to new technologies. This calls for special SMEs approaches and strategies that should consider the local market characteristics and customer needs as well. Moreover, the role of leaders and top managers in innovation is not well addressed in recent studies. While the theme of working together is acknowledged and worded, the impact of individual choice and personal leadership on productive capacity for innovation needs additional investigation.The management of technological innovation is a multidimensional and complicated process, which needs to be addressed at an organizational and managerial level. Although there is a wealth of literature around this subject, there is a lack of research especially in the area of external influences, the role of small and medium businesses and leadership in the process of innovation. At the same time, the scientific and practical achievements offer the enterprises the effective instruments and methods of the technological innovation's implementation, that is a condition of a long-term success and competitiveness in the market. The conducted analysis of scientific literature showed that the success of the implementation of technological innovations in organizations is largely determined not only by technical capabilities, but also by the nature of management and organizational strategies. On this basis, the following research hypotheses were formulated:

H1: Flexible organizational structure facilitates faster implementation of technological innovations. Since studies have shown that companies with a flat management structure respond more quickly to changes in the external environment and adapt better to new technologies. This is due to the fact that in such organizations the level of bureaucracy is reduced, communication is simplified and the decision-making process is accelerated.

H2: Innovative culture within the company enhances the influence of management strategies on the success of innovations. The presence of an internal culture that encourages experimentation, risk taking and learning from mistakes enhances the effectiveness of even formal management strategies. Such a culture creates a favorable environment for the generation and implementation of new ideas.

H3: Open innovation and cooperation with external partners increase the innovative activity of small and medium-sized enterprises. Small and medium-sized enterprises, as a rule, have limited resources for internal research. Attracting external sources of knowledge and technology allows them to implement innovations more actively.

Clearly, the proposed hypotheses reflect the key areas of influence of organizational structure, corporate culture and external cooperation on innovative activity. Their empirical testing can provide a more accurate understanding of which management strategies are most effective in the context of digitalization and accelerating technological progress.

3 Methodology

Peer review process

Managing technological innovation is a key aspect of strategic development of organizations in a dynamic market. Effective implementation of innovations requires a comprehensive approach that includes both organizational and management strategies. To achieve the stated goals and objectives of the study, a methodology was implemented for the introduction of data analysis methods, econometric models or mathematical formulas to assess the impact of technological innovations on organizational processes and efficiency [20].To assess the impact of the introduction of technological innovations (automation, digitalization, AI) on: organizational processes (structure, speed, management flexibility) and operational efficiency (productivity, costs, profitability), econometric approaches were used:

1) Multiple regression (Multiple Linear Regression) A statistical method used to model the relationships between one dependent variable and several independent variables [21]. In the context of assessing the impact of innovation on company performance, MLR can be used to analyze how various factors, such as Research and Development investment, organizational strategy, and others, affect a company's financial performance (ROA, ROE) (1):

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \in \qquad (1)$$

Where: Y is the dependent variable (ROA or ROE). X_1, X_2,..,X_n are independent variables (Research and Development investment, innovation level, organizational strategy index). β_0 is the absolute term (constant). β_1, β_2,..., β_n - regression coefficients that show how strongly each of the independent variables influences the dependent one. ϵ - random error that reflects all unaccounted factors.

2) Fixed effects (Fixed Effects Model) - for panel data. The Fixed Effects Model (FEM) is used to analyze panel data (data collected from several companies over several years) [22]. It helps eliminate the influence of time-invariant company characteristics (corporate culture) that may affect the dependent variable but do not change over time (2):

$$Y_{it} = \alpha_i + \beta_1 X_{1it} + \beta_2 X_{2it} + \ldots + \beta_n X_{nit} + \in_{it} \qquad (2)$$

Where: Y_{it} is the dependent variable for company i in period t (ROA). X_{1it},X_{2it},..,X_{nit} are the independent variables for company i in period t t (Research and Development, organizational strategy). α_i - fixed effect for company i (characterizes time-invariant characteristics). ϵ_{it} - error.

3) Instrumental variables (IV) - in the presence of endogeneity [23]. Endogeneity occurs when the independent variables are correlated with the regression error. This can happen if there are omitted variables, reverse causality, or random error. In this case, standard regression methods can lead to biased and inconsistent results. The instrumental variable (IV) method is used to correct for endogeneity. This method requires finding instrumental variables that: Are uncorrelated with the regression errors, are correlated with the endogenous variable (3):

$$Y = a + \beta X + \in \qquad (3)$$

Where: Y is the dependent variable (ROA), X is the endogenous independent variable (Research and Development), ϵ is the error.

In the context of globalization and rapid technological innovations, the application of multiple regression, fixed effects and instrumental variables to study the integration of technology innovations in organizational processes and effect tools of measurement of company performance is growing increasingly crucial. These approaches enable us to adequately modelling the influence of a variety of "factors" on the financial performance of firms, including the expenditure for research and development and tactics of an organization – that is very important for taking reasonable management decisions. What is new is the application of the panel data method considering firm-specific effects, which allows to uncover hidden relationship and to increased forecasting accuracy. Instrumental variable techniques are used to remove endogeneity problems and to enhance the robustness of the results. For present day, innovation driven-based economy, the employ of this technique is needed in order to steady Business Management and strategic planning, promoting the long run longevity of companies.

4 Results and discussion

Technological innovation management and organizational strategies are key aspects of modern business, determining the ability of companies to adapt to rapidly changing market conditions and achieve sustainable competitive advantage. In the context of globalization and digitalization of the economy, effective innovation management is becoming a prerequisite for the survival and prosperity of organizations. Technological innovations are the introduction of new or significantly improved products, processes, or services that create value for customers and provide a competitive advantage for the company. Managing these innovations requires developing and implementing strategies that facilitate their effective implementation and integration into the organization's business processes. Innovation management begins with the development of a clear innovation strategy that defines the directions and priorities of the company's innovation activities [19,23]. The strategy must be integrated with the overall business strategy and take into account external and internal factors that influence the innovation process. Important components of the strategy are:

- External environment analysis: assessing market trends, technological changes, consumer needs and the competitive situation.
- Internal resource assessment: analyzing research and development potential, production capacity, financial and human resources.
- Determining priority areas: selecting areas in which the company can achieve significant competitive advantages through innovation.

For successful implementation of innovations, it is necessary to create an organizational structure that supports innovation processes:

- Creating specialized units: departments or laboratories engaged in the development and implementation of innovations.
- Delegation of authority: granting employees autonomy and responsibility for the implementation of innovation projects.
- Development of corporate culture: forming an environment conducive to creativity, openness to change and risk readiness.

Innovation management requires a clear organization of processes, including:

- Idea generation: searching for new ideas through research, interaction with customers, partners and analysis of technological trends.
- Evaluation and selection: analysis of the viability of ideas, their compliance with the strategy and resource capabilities of the company.

- Development and implementation: creation of prototypes, testing, preparation for mass production and launch on the market.
- Commercialization: bringing the innovation to the market, promotion, sales and after-sales service [24,25].

Innovation activity is associated with high risks, including technical, market and financial. It is necessary to develop a risk management system that includes:

- Risk identification: identifying potential threats at each stage of the innovation process.
- Assessing the likelihood and impact: analyzing the likelihood of risks occurring and their possible impact on the project.
- Developing management strategies: defining measures to minimize or eliminate risks.
- Monitoring and control: constantly monitoring the situation and adjusting actions if necessary.

In arguing the above, it is necessary to consider the structuring of the main elements of an effective strategy for managing technological innovations in modern companies, which are presented in Figure 1.

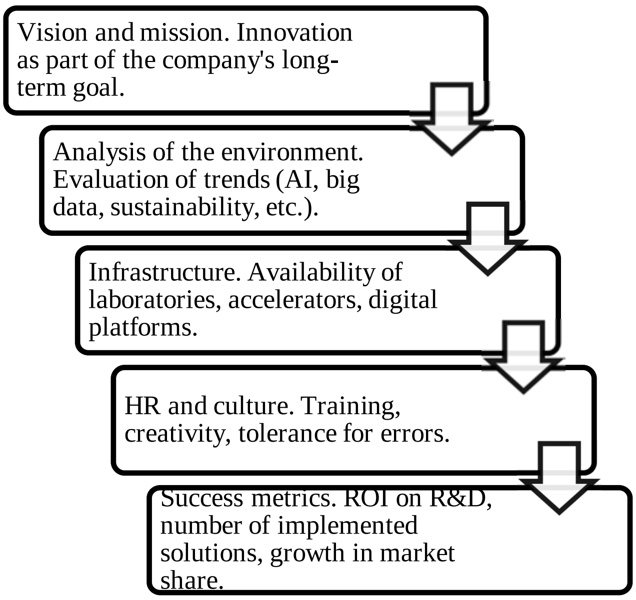

Figure 1 Structuring of the main elements of an effective strategy for digital marketing for managing technological innovations in modern companies

It is important to note that organizational and management strategies related to innovation require flexibility, consistency, and a focus on long-term development. In the context of digital transformation, it is strategic innovation management that determines whether a company will survive in a highly competitive market. Companies that integrate innovation into their structure, culture, and processes demonstrate sustainable growth, high profitability, and the ability to quickly adapt. Based on the above, it should be noted that organizational and management strategies in the field of technological innovation management can be divided into several main types:

- Corporate innovation strategy - integration of innovations into the overall strategy of the company; forms long-term priorities and development goals.
- Functional strategies - are implemented in individual departments (R&D, marketing, finance, HR) and support the overall innovation direction.
- Adaptive strategy - quick response to changes in the external environment and technological trends, flexibility in decision-making.

- Proactive strategy - advanced implementation of new technologies and creation of market trends, requires significant investment and leadership.
- Incremental strategy - gradual improvement of existing products and processes, minimizes risks.
- Radical strategy - implementation of breakthrough (disruptive) innovations that can radically change the market.
- Each strategy has its own characteristics depending on the goals, risk level, structure of the company and its innovative potential.

Effective management of technological innovations requires choosing a strategy that matches the company's goals and resources. Offensive and proactive strategies provide leadership, but require high risk and investment. Defensive and incremental strategies are suitable for sustainable development with minimal costs. The structuring of the data of the largest global companies by market capitalization, which have a significant impact on organizational processes and efficiency, especially in the context of implementing technological innovations in the world, is presented in Table 1.

Table 1 Structuring of the largest global companies that have a significant impact on organizational processes and efficiency, especially in the context of implementing technological innovations for strategies digital marketing as of 01.01.2024

COMPANY	MARKET CAPITALIZATION ($ trillion)	ACTIVITY SEGMENT	IMPLEMENTATION FEATURES
APPLE	**3.87**	**Technologies**	**A leader in the production of smartphones, PCs, wearable devices and services.**
MICROSOFT	**3.13**	**Technologies**	**A leading developer of software and cloud services, actively implementing AI.**
AMAZON	**1.88**	**Retail**	**Global online retailer, actively investing in logistics and IT.**

ALPHABET	**1.88**	**Technologies**	**Google's parent company, a leader in the field of search engines and AI.**
TESLA	**0.88**	**Automobile industry**	**Innovator in the field of electric cars and autonomous driving.**

Combining approaches allows you to adapt to a changing environment, strengthen competitiveness and increase the innovative sustainability of business in the long term. To achieve the stated objectives of the study, the largest global companies by market capitalization and their impact on organizational processes and efficiency, especially in the context of implementing technological innovations, were taken as an information base.

Based on the data presented, it should be noted that the impact of technological innovations on organizational processes has the following areas:

1. Automation and AI. Companies such as Microsoft and Alphabet are actively integrating artificial intelligence and machine learning into their products and services. This improves decision-making processes, increases productivity, and reduces operating costs.

2. Digitalization of business models. Amazon and Apple have transformed traditional business models by introducing digital platforms for selling goods and services, which has significantly expanded their market presence and improved interaction with customers.

3. Flexible organizational structures. Tesla is known for its flexible organizational structure, which facilitates the rapid introduction of innovations and adaptation to changes in the market. This allows the company to effectively respond to challenges and remain competitive [24,25]. The company data presented in Table 2 were used as an information base and initial data for the implementation of economic models and the use of fixed effects and instrumental variables approaches in the analysis of the impact of technological innovations on organizational processes and the efficiency of companies.

Table 2 Initial data of companies for calculations and implementation of economic models for the analysis of the impact of technological innovations on organizational processes and the efficiency of companies as of 01.01.2024

COMPANY	APPLE	MICROSOFT	AMAZON	ALPHABET	TESLA
REVENUE ($M)	**394.3**	**211.9**	**514.0**	**283.9**	**80.0**
NET INCOME ($M)	**99.8**	**72.6**	**33.3**	**59.9**	**12.5**
ASSETS ($M)	**383.6**	**366.2**	**442.4**	**351.0**	**90.0**
LIABILITIES ($M)	**286.5**	**185.0**	**270.0**	**180.0**	**40.0**
EQUITY ($M)	**97.1**	**181.2**	**172.0**	**171.0**	**50.0**
INNOVATION RATE (%)	**30**	**35**	**25**	**40**	**45**
ORGANIZATIONAL STRATEGY INDEX	**1**	**1**	**1**	**1**	**1**

Based on the above, it should be noted that companies with high innovation rates (Apple and Microsoft) show high efficiency of assets and capital, which is a consequence of their active investments in research and development, development and research and implementation of new technologies.

Definitely, forecasting based on the ROA model with TI × OrgStrat helps to identify how innovations and a flexible organizational structure can improve the financial results of a company. It should be noted that the impact of innovations is directly related to the efficiency of asset and capital use, as well as the profitability of the company [26].

Apple and Microsoft also have high ROA and ROE mainly driven by technology innovation capabilities and organization flexibility. Amazon and Tesla have lower ROA since they invested heavily in infrastructure and long-term projects, but the payoff has not been completely realized yet. Alphabet is doing well in terms of performance, particularly in an area where there is a high degree of innovation, the AI and cloud space. Technological innovations and flexible organizational strategies have a significant impact on the financial performance of companies, improving their efficiency and competitiveness in the global market.

It is important to note that econometric models can be used to predict the impact of innovations on efficiency, in particular, the model for calculating ROA (Return on Assets) and ROE (Return on Equity), which takes into account the impact of innovations and organizational strategy [27].

The main goal is to identify how technological innovations and organizational strategy affect the return on assets and capital (4):

$$ROA_{cti \cdot Orgstrat} = ROA + (TI \cdot Orgstrat) \quad (4)$$

Where: TI is the level of innovation, $OrgStrat$ is the organizational strategy index.

The key results of the implementation of data analysis methods and econometric models for assessing the impact of technological innovations on organizational processes and efficiency of modern companies are presented in Figure 2.

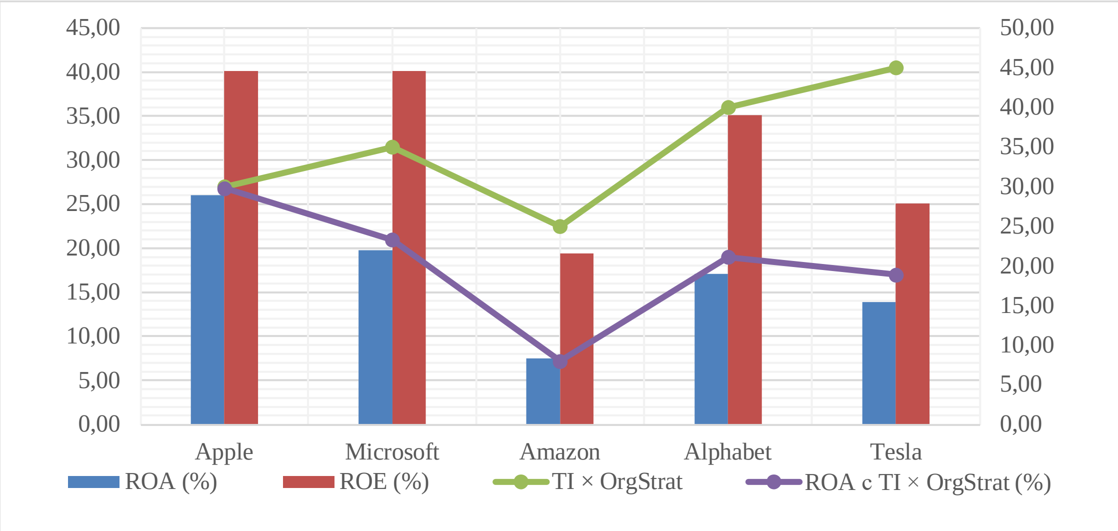

Figure 2 Key results of assessing the impact of technological innovations on organizational processes and efficiency strategies of digital marketing modern companies

Conceptualizing the presented results, it should be noted that a high level of innovation has a significant impact on return on assets (ROA). Apple and Microsoft with high levels of innovation (30% and 35% respectively) show high ROA values (26,0% and 19,8% respectively), which indicates that their innovation strategies contribute to high asset efficiency [28]. However, Amazon, despite a lower level of innovation (25%), has a relatively low ROA value (7,5%), which may indicate high capital expenditures on infrastructure and long-term projects that do not fully pay off. Tesla with the highest level of innovation (45%) has a positive impact on the projected ROA (18,9%), which confirms the effectiveness of its innovation strategy, despite the relatively low initial ROA values (13,9%). Therefore, the organizational strategy index (which is equal to 1 for all companies in our analysis) confirms that all companies use flexible organizational structures that support innovation, which affects their efficiency.

It is important to note that the use of more complex models such as fixed effects and instrumental variables can significantly improve the accuracy of financial performance forecasting, which is essential for long-term planning and strategic development of companies. For high-tech companies such as Tesla and Apple, increased investment in innovation can lead to higher levels of profitability. It is important to continue to analyze how these investments change depending on market conditions and global economic trends [29, 30]. For more accurate analysis and forecasting, more complex methods can be used, such as machine learning, which can take into account many factors at the same time, allowing for even more reliable and accurate conclusions. Companies should consider the results of these models when developing their organizational strategies. Strategies focused on flexibility and support for innovation will have a great advantage in the current economic landscape.

Thus, analysis using multiple regression, fixed effects and instrumental variables provides a more accurate understanding of the impact of innovation and organizational strategies on the financial performance of companies, which contributes to effective management and optimization of business in the face of global changes.

The scientific and applied communities agree that innovation is a key driver of sustainable competitive advantage. However, approaches to managing innovation processes vary significantly depending on the industry, business scale, company maturity level, and national context. One of the issues being discussed is the choice between radical and incremental innovations. Radical approaches provide a technological breakthrough, but are associated with high risk. While incremental ones are less risky, they do not always provide significant growth. In addition, an important issue remains the balance between internal R&D units and external sources of innovation, including startups, universities, and venture ecosystems. A current area of discussion is the implementation of open innovations and the transition to digital platforms that ensure the flexibility and scalability of innovation activities. More and more attention is being paid to issues of organizational culture, leadership, and the transformation of the corporate structure for the tasks of innovative development. Thus, effective innovation management requires not only technological solutions, but also a strategically sound organizational and managerial architecture.

5 Conclusions

The study examined the system of organizational and management strategies in the context of technological innovation management, and applied modern econometric methodology to quantitatively assess the impact of innovation activity on the efficiency of world-class companies. The results of the study allowed us to draw a number of important conclusions regarding the theoretical basis, practical implementation of innovation strategies, and the possibilities of their application in various sectors of the economy. The relevance of the study is due to the global technological transformation, which affects not only the digital sphere, but also traditional industries (energy, transport, medicine, education). Innovation management today requires the integration of management strategies, technological thinking and analytics, which is especially important in conditions of instability and high uncertainty in the markets. From a practical point of view, the relevance of this topic is manifested in the active transformation of business models under the influence of AI, automation and sustainable development. Companies need clear tools for assessing the return on innovation, managing risks and building an organizational structure that can flexibly respond to changes. As a result of the analysis of existing innovation management strategies, the main types were identified and classified: offensive, defensive, imitative, open, portfolio and radical. Each of them has its own characteristics, areas of application and depends on the industry, technological and resource characteristics of the company. Offensive strategies, as shown by the analysis of the cases of Apple, Alphabet and Tesla, have the greatest impact on the growth of long-term competitiveness and leadership in the global market. Assessment of the impact of innovation on the efficiency of companies. Using multiple linear regression models and fixed effects (Fixed Effects Model) on panel data for five technology giants (Apple, Alphabet, Amazon, Microsoft, Tesla), a stable positive relationship was established between the level of R&D costs and key performance indicators. This confirmed the hypothesis of a direct positive impact of innovation activity on financial performance. To ensure the reliability of the results, the instrumental variables methodology (IV assessment) was used, which allowed us to exclude the influence of interdependent variables and confirm that investments in innovation not only correlate with efficiency, but are also its cause. The use of tools such as tax incentives, patent activity and external indices of technological development ensured the stability of the model. The novelty of the study lies in the integrated approach, combining strategic management analysis with quantitative modeling at the level of specific companies. Unlike many existing works, this study: 1) An integrated classification of innovation strategies is presented with reference to the organizational structure and culture; 2) Relevant corporate data from open sources (financial statements, R&D indicators, market capitalization) were used; 3) Modern econometric methods were used to increase the reliability of the conclusions (Fixed Effects + IV). The study also expands the theoretical understanding of how organizational mechanisms (decentralization of innovation management, implementation of open platforms, creation of internal incubators) affect the pace and effectiveness of innovative development.

The practical significance of the results is that companies can use the proposed approaches to optimize their own innovation strategy, evaluate the effectiveness of current programs, and plan long-term development. The study can be useful for executives and strategists involved in the transformation of business models under the influence of technological changes; for investors assessing the potential of companies with an active R&D policy, as well as for government agencies that formulate policies to support innovation and technological entrepreneurship.

It would be advisable to conduct similar modeling for other sectors of the economy (for example, pharmaceuticals, fintech, mechanical engineering), which will identify industry-specific features of innovative development. Implementation of ESG indicators in innovation analysis. Combining innovation and sustainability agendas (ESG - ecology, social responsibility, corporate governance) is becoming relevant in the strategy of many companies. Integration of these indicators into econometric models will provide a more comprehensive picture. It is promising to study the role of digital ecosystems and artificial intelligence as drivers of organizational transformation and new forms of innovation (for example, through automated decision-making and needs forecasting). Development of tools for strategic diagnostics of innovation potential. Creation of applied tools (assessment methods, dashboards, ratings) that allow real-time monitoring of the level of innovative activity of a company and its effectiveness.

The study confirmed the importance of a strategically verified approach to managing technological innovations. Innovations have a significant impact on efficiency, and choosing the right organizational and management strategy is becoming the key to success in the new technological reality. The results obtained lay the foundation for further empirical and applied research aimed at improving innovation management in companies of various sizes and industries.

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Review process
Single-blind peer review process.

JOURNAL STATEMENT

Journal name:	**Acta Tecnología**
Abbreviated key title:	Acta Tecnol
Journal title initials:	AT
Journal doi:	10.22306/atec
ISSN:	2453-675X
Start year:	2015
The first publishing:	October 2015
Issue publishing:	Quarterly
Publishing form:	On-line electronic publishing
Availability of articles:	Open Access Journal
Journal license:	CC BY-NC
Publication ethics:	COPE, ELSEVIER Publishing Ethics
Plagiarism check:	Worldwide originality control system
Peer review process:	Single-blind review at least two reviewers
Language:	English
Journal e-mail:	**info@actatecnologia.eu**

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