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A Message from the Editor-in-Chief

The Serbian Journal of Engineering Management is a scientific journal published by the School of Engineering Management and the Society of Engineering Management of Serbia. The journal is classified by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia. It has been indexed in EBSCO databases since 2020 and included in the ERIH PLUS list since 2023. This international journal is dedicated to a wide range of themes in engineering management and industrial engineering and is published twice a year, in January and July. Papers are published in Serbian or English.

As in previous issues, this issue brings together contributions spanning the many fields within the journal's scope, from technical reliability and engineering systems to public health, communication, education, leadership, and marketing. This breadth is not incidental: engineering management today rarely unfolds within a single discipline, and the value of a journal such as this lies precisely in its ability to hold that diversity together within a single, coherent whole.

The editorial board comprises distinguished academics from a number of countries, dedicated to establishing the highest academic standards and promoting the principles of engineering management in Serbia.

We remain grateful to our authors and reviewers, whose patient, often invisible work is what allows the journal to keep its promise, issue after issue.

Further information about the journal, in both English and Serbian, can be found at: https://fim.edu.rs/publishing/journal.

Prof. Dr. Vladimir Tomašević, FRSA

Reč glavnog urednika

Serbian Journal of Engineering Management je naučno-stručni časopis koji izdaju Fakultet za inženjerski menadžment i Društvo inženjerskog menadžmenta Srbije. Časopis je kategorisan od strane Ministarstva nauke, tehnološkog razvoja i inovacija Republike Srbije. Od 2020. godine indeksiran je u EBSCO bazama, a od 2023. godine nalazi se i na ERIH PLUS listi. Ovaj međunarodni časopis posvećen je širokom spektru tema iz oblasti inženjerskog menadžmenta i industrijskog inženjerstva i izlazi dva puta godišnje, u januaru i julu. Radovi se objavljuju na srpskom ili engleskom jeziku.

Kao i u prethodnim brojevima, ovaj broj okuplja radove iz mnogih oblasti koje ulaze u širi okvir časopisa, od tehničke pouzdanosti i inženjerskih sistema do javnog zdravlja, komunikacija, obrazovanja, liderstva i marketinga. Ta raznovrsnost nije slučajna: inženjerski menadžment se danas retko odvija unutar jedne discipline, a vrednost ovakvog časopisa upravo je u tome što on tu raznovrsnost objedinjuje u jednu koherentnu celinu.

Uredništvo časopisa čine istaknuti naučnici iz različitih zemalja sveta, posvećeni postavljanju najviših akademskih standarda i promociji principa inženjerskog menadžmenta u Srbiji.

Zahvalni smo našim autorima i recenzentima, čiji strpljivi, često nevidljivi rad omogućava da časopis iz broja u broj ispuni ono što obećava.

Dodatne informacije o časopisu, na srpskom i engleskom jeziku, dostupne su na: https://fim.edu.rs/publishing/journal.

Prof. dr Vladimir Tomašević, FRSA

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Pregled metoda prediktivnog održavanja zasnovanih na veštačkoj inteligenciji za degradaciju i pouzdanost lopatica gasnih turbina

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Apstrakt: Gasnoturbinski motori predstavljaju ključne pogonske sisteme u savremenoj vazduhoplovnoj industriji, pri čemu turbinski delovi rade u ekstremnim eksploatacionim uslovima koje karakterišu visoke temperature, velika centrifugalna naprezanja i agresivno gasno okruženje. Turbinske lopatice, kao najkritičnije i najopterećenije komponente, izložene su kombinovanom delovanju termičkih i mehaničkih opterećenja, što dovodi do razvoja složenih mehanizama degradacije materijala.
U ovom preglednom radu razmatra se ponašanje turbinskih lopatica u uslovima dugotrajne eksploatacije, sa posebnim osvrtom na dominantne mehanizme degradacije, kao što su puzanje, oksidacija, termički i visokociklični zamor, kao i mikrostrukturne promene koje prethode inicijaciji i propagaciji pukotina.
Posebna pažnja posvećena je mogućnostima primene savremenih metoda veštačke inteligencije u okviru okvira prediktivnog održavanja, sa fokusom na procenu preostalog radnog veka (RUL), detekciju anomalija i analizu obrazaca degradacije. Rad daje kvalitativni pregled mehanizama degradacije materijala i pristupa prediktivnog održavanja zasnovanih na veštačkoj inteligenciji, uz naglašavanje njihovog potencijalnog doprinosa unapređenju pouzdanosti vazduhoplovnih sistema.

Ključne reči: gasnoturbinski motori, mikrostrukturna degradacija, prediktivno održavanje, preostali radni vek (RUL)

A Review of AI-Based Predictive Maintenance Methods for Gas Turbine Blade Degradation and Reliability

Abstract: Gas turbine engines represent key propulsion systems in the modern aerospace industry, with their turbine section operating under extreme service conditions characterized by high temperatures, significant centrifugal stresses, and aggressive gaseous environments. Turbine blades, as the most critical and highly loaded components, are subjected to combined thermal and mechanical loading, leading to the development of complex material degradation mechanisms.
This review discusses the behavior of turbine blades under long-term service conditions, with particular emphasis on dominant degradation mechanisms such as creep, oxidation, thermal and high-cycle fatigue, as well as microstructural changes preceding crack initiation and propagation.
Special attention is given to the potential application of modern artificial intelligence methods within predictive maintenance frameworks, focusing on remaining useful life (RUL) estimation, anomaly detection, and the analysis of degradation patterns. The paper provides a qualitative overview of material degradation mechanisms and AI-based predictive maintenance approaches, highlighting their potential role in supporting reliability improvement in aerospace systems.

Keywords: gas turbine engines, microstructural degradation, predictive maintenance, remaining useful life (RUL)

1. Introduction

Aerospace systems represent one of the most complex classes of engineering systems, in which safety, reliability, and material degradation management are of critical importance. In the modern aerospace industry, gas turbine engines occupy a central role as propulsion systems, operating under conditions of high thermal, mechanical, and aerodynamic loads, as well as stringent requirements in terms of reliability and operational availability.

A particularly critical region is the turbine section of the engine, especially the turbine blades located in the hot section. The "hot section" of a gas turbine engine refers to the combustion chamber and turbine stages, which operate under extremely high temperature conditions and represent the zone of most intensive thermal and microstructural material degradation. During operation, these components are exposed to high temperatures, significant centrifugal stresses, and an aggressive gas environment, making them the most highly loaded and critical elements from the standpoint of material degradation and failure initiation.

The reviewed literature indicates that dominant degradation mechanisms include creep, oxidation, thermal fatigue, high-cycle fatigue, and thermo-mechanical fatigue (Kurz & Brun, 2000). These processes lead to progressive deterioration of the material microstructure, with Ni–Cr-based superalloys being widely used due to their high-temperature resistance, although they remain susceptible to long-term degradation. Microstructural damage, such as intergranular cracking and grain boundary weakening, represents a key indicator of progressive failure. Therefore, continuous monitoring of turbine blade condition is essential for reliability assessment and failure prevention.

Advances in sensor technologies and condition monitoring systems have enabled a transition from traditional maintenance strategies based on fixed intervals to condition-based and predictive maintenance approaches. Preventive maintenance relies on predefined schedules, whereas predictive maintenance utilizes real-time operational data to assess component health and estimate Remaining Useful Life (RUL), often supported by machine learning and data-driven methods.

The literature used in this study was identified through a structured search of scientific databases, including Scopus, Web of Science, and Google Scholar. The initial search was performed using combinations of keywords such as "gas turbine blade degradation", "remaining useful life", "predictive maintenance", "prognostics and health management", "condition monitoring", and "artificial intelligence in maintenance".

In addition to the database search, a snowballing approach was applied to ensure a comprehensive coverage of relevant literature. This included backward citation tracking (screening reference lists of selected papers) and forward citation tracking using Google Scholar's "cited by" and recommendation features. This approach enabled the inclusion of both recent studies and earlier seminal works that form the theoretical foundation of gas turbine degradation and reliability analysis.

The review therefore includes a combination of recent publications (2005–2025), primarily focused on artificial intelligence and predictive maintenance methods, as well as earlier foundational studies addressing gas turbine degradation mechanisms and material behavior. Preference was given to peer-reviewed journal articles and conference papers written in English. The search results were screened based on titles, abstracts, and full texts to select studies relevant to the research focus.

2. Operating Conditions and Degradation of Gas Turbine Blades

Gas turbine engines represent key propulsion systems in modern aerospace engineering, with their turbine components operating under extreme service conditions characterized by high temperatures, large centrifugal stresses, and aggressive gas environments (Mattingly, 2002; Saravanamuttoo et al., 2001). Turbine blades, as the most critical and highly loaded components, are located in the hot section of the engine and are exposed to severe thermal conditions. Gas temperatures typically range from approximately 800 °C in the early stages to values exceeding 1000–1100 °C in high-pressure turbine sections, depending on engine design and cooling efficiency (Behera et al., 2023). Higher overall gas-path temperatures, reaching up to approximately 1300 °C, have also been reported in gas turbine systems (Bohidar et al., 2013). In localized hot-spot conditions, metal temperatures may further increase and approach or exceed 1200 °C, making these components particularly susceptible to progressive material degradation and failure initiation.

Under such conditions, complex degradation mechanisms occur, including creep, oxidation, thermal fatigue, high-cycle fatigue, and thermo-mechanical fatigue. Experimental studies on service-exposed turbine blades have shown

that long-term exposure to elevated temperatures leads to γ′ precipitate coarsening and rafting, carbide transformation, grain boundary degradation, and crack initiation, resulting in progressive deterioration of mechanical properties and reduced blade life (Najmi & Migbagheri, 2023; Kolagar et al., 2017). These processes lead to gradual deterioration of the material microstructure and are recognized as the primary causes of progressive turbine blade damage. In addition, erosion and fouling phenomena significantly influence component performance by altering blade geometry and surface condition, thereby affecting aerodynamic flow characteristics through the turbine (Kurz et al., 2000; Kurz et al., 2014).

Nickel (Ni) based alloys with chromium (Cr) play a particularly important role due to their high-temperature resistance; however, they still exhibit significant sensitivity to long-term operational loading. Their degradation is manifested through microstructural changes, including phase coarsening, grain boundary weakening, and intergranular damage (Sujata et al., 2010). Furthermore, the interaction of airborne particles with blade surfaces leads to erosive wear, the intensity of which depends on particle velocity, impact angle, and temperature, and can be predicted using numerical simulations of particle trajectories in a three-dimensional flow field (Tabakoff et al., 1998).

In real operational conditions, additional contributions to degradation arise from oxidation and thermal corrosion, as well as the initiation and propagation of microcracks along grain boundaries. These phenomena represent direct indicators of deteriorated operating conditions and often precede catastrophic blade failure (Ejaz, 2006). Moreover, increased clearances and sealing system degradation result in additional losses and flow disturbances, thereby affecting overall turbine performance (Kurz et al., 2000).

Therefore, monitoring component condition and understanding degradation mechanisms are of critical importance for reliability assessment and maintenance planning. In this context, modern approaches include the development of both simplified and complex models for degradation simulation, as well as methods for detecting performance changes during operation (Kurz et al., 2000; Kurz et al., 2014). In addition, the application of protective coatings, such as ceramic and metallic layers deposited using advanced processes (e.g., CVD), has proven to be an effective method for reducing erosive wear and extending blade service life (Tabakoff et al., 1998).

3. Traditional and modern maintenance approaches

Maintenance of gas turbine engines in aviation has traditionally been based on preventive and corrective strategies, which form the foundation of airworthiness and system safety management. Preventive maintenance involves scheduled interventions at predefined time or cycle intervals, independent of the actual condition of components, whereas corrective maintenance is performed after failure occurrence.

The periodicity of preventive maintenance for gas turbine engines can be determined using multi-criteria decision analysis methodologies (Biocanin et al., 2024) or reliability-based models (Biocanin, 2024).

In the case of turbine blades, such approaches have significant limitations, as material degradation is a continuous and progressive process that cannot always be reliably detected through discrete inspections. In practice, technical diagnostic methods such as visual inspections, non-destructive testing (NDT), and service data analysis are used to assess component condition; however, these methods are limited by inspection intervals and subjective interpretation.

Aircraft maintenance is largely governed by regulatory requirements of the European Union Aviation Safety Agency (EASA), particularly through regulations such as Part-M and Part-145, which define inspection procedures, maintenance actions, and documentation requirements. Although these standards ensure a high level of safety, they are primarily based on conservative assumptions regarding degradation and predefined maintenance intervals.

For this reason, condition-based maintenance (CBM) and predictive maintenance approaches are gaining increasing importance in modern practice. These concepts may support decision-making based on the actual condition of components, supported by continuous monitoring of operational parameters. This is particularly important for components such as turbine blades, where degradation directly affects system reliability and safety. The evolution of maintenance strategies in aviation, from traditional approaches to modern data-driven and AI-based methods, is illustrated in Figure 1.

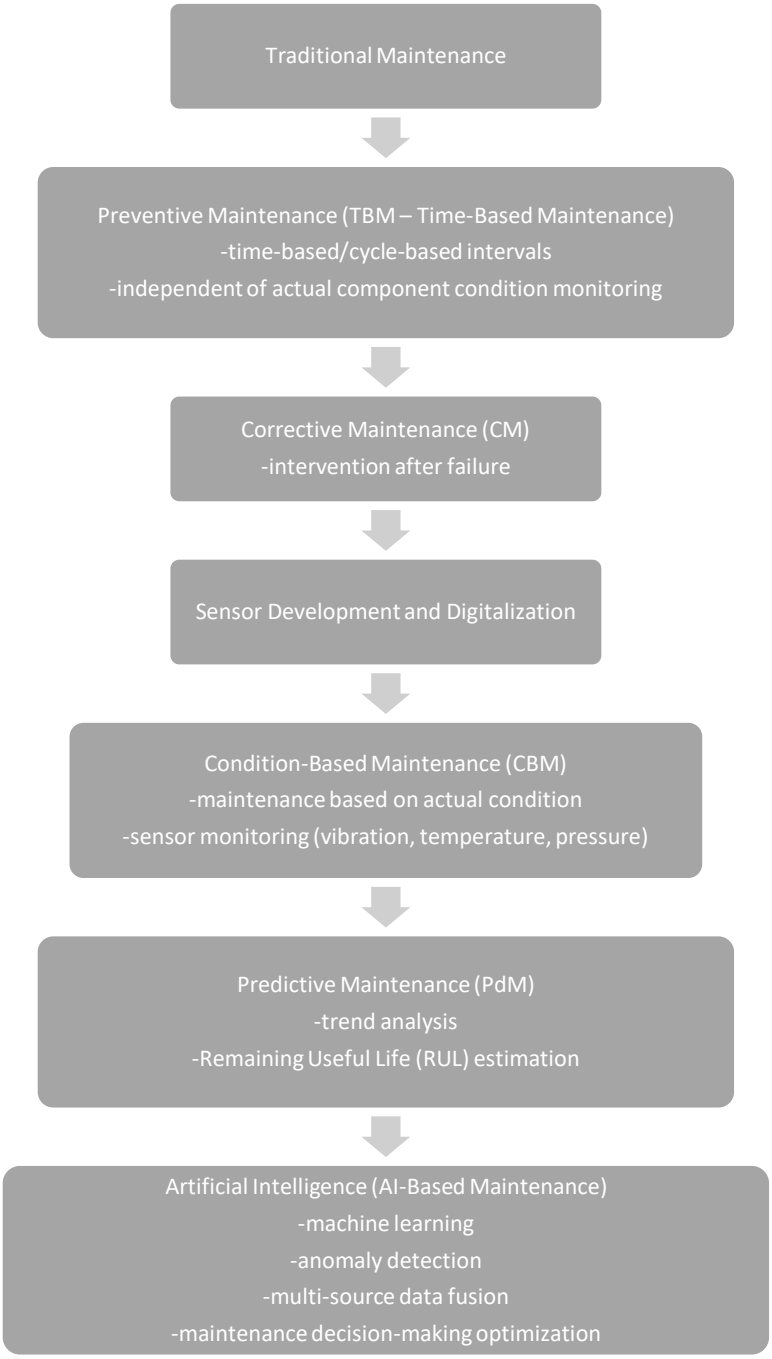

Figure 1: Conceptual framework of AI-based predictive maintenance for turbine blade degradation (Data generated by the authors)

4. Application of artificial intelligence in predictive maintenance

Artificial intelligence represents a key tool for analyzing data collected during the operation of gas turbine engines, including temperature regimes, vibrations, pressures, and other parameters relevant to assessing the condition of turbine blades.

This paper does not aim to develop or experimentally validate specific artificial intelligence algorithms, but rather to provide a qualitative and conceptual overview of their potential application within predictive maintenance frameworks.

Within these approaches, machine learning methods reported in the literature show potential for identifying degradation patterns that are not always detectable using classical analytical techniques. A broad overview of machine learning- and deep learning-based approaches for fault diagnosis and prognostics in industrial systems has been extensively discussed in the literature (Lei et al., 2018; Zonta et al., 2020), particularly in the context of predictive maintenance and Industry 4.0 applications. The most commonly applied techniques include neural networks, decision tree–based methods (random forest—an ensemble method that combines multiple decision trees to achieve more robust classification), and support vector machines (an algorithm that determines the optimal hyperplane separating classes in the data space), which have been applied for anomaly detection, state classification, and degradation trend analysis.

Modern approaches within Prognostics and Health Management (PHM) are based on the integration of physical degradation models and machine learning methods. Such hybrid models may support more reliable condition assessment by combining an understanding of degradation mechanisms with operational data analysis. The PHM and condition-based maintenance (CBM) framework has been widely established as a structured approach for maintenance optimization in engineering systems (Jardine et al., 2006; Tsui et al., 2015). A particularly important aspect is the estimation of Remaining Useful Life (RUL), where historical and real-time data are used to predict the time to failure. This approach represents one of the key concepts of predictive maintenance and may support optimization of maintenance intervals, especially for components exposed to intensive degradation such as turbine blades (Szrama et al., 2025).

Experimental investigations of service-exposed turbine blades have shown that microstructural evolution, hardness variation, and degradation of mechanical properties are strongly correlated with service exposure time, emphasizing the importance of degradation monitoring for RUL estimation and predictive maintenance strategies (Li et al., 2023). A structured overview of commonly applied artificial intelligence methods in predictive maintenance, including their applications, input data, expected outputs, advantages, and limitations, is presented in Table 1.

Table 1: Overview of AI methods in predictive maintenance of gas turbine engines

AI Method	Application	Input Data	Output	Advantages	Limitations
Neural Networks	Remaining Useful Life (RUL) prediction	Temperature, vibration, pressure	Time to failure	Models nonlinear degradation; suitable for time-series data	Limited interpretability; large datasets required
Random Forest	Fault detection and classification	Sensor data, operational parameters	Fault type/health state	Robust to noise and overfitting	Limited temporal sequence modeling
Support Vector Machine (SVM)	System health classification	Engine performance parameters	Health state category	Good performance in high-dimensional spaces	Sensitive to parameter selection

Table 2 presents a synthesized relationship between dominant turbine blade degradation mechanisms, observable operational indicators, typical input data, and corresponding artificial intelligence applications within predictive maintenance frameworks. The table is compiled based on findings reported in the literature on gas turbine degradation and condition monitoring systems (Mattingly, 2002; Saravanamuttoo et al., 2001; Kurz et al., 2014; Viswanathan, 2006). As shown, different degradation processes can be associated with specific measurable parameters obtained from engine monitoring systems, including temperature, vibration, pressure, and operational cycle data. The reviewed literature suggests that AI-based methods may support the identification of degradation trends, anomaly detection, fault classification, and Remaining Useful Life (RUL) estimation, depending on the type of degradation mechanism and available data sources.

Table 2: Synthesized relationship between turbine blade degradation mechanisms, observable indicators and AI-based predictive maintenance tasks (compiled by the authors based on reviewed literature)

Degradation mechanism	Observable indicators	Typical input data	AI task/application
Creep	Progressive deformation, temperature increase	Temperature history, operating cycles	Remaining Useful Life (RUL) estimation
Oxidation / thermal corrosion	Surface degradation, efficiency loss	Temperature data, exhaust gas parameters	Anomaly detection
High-cycle fatigue	Vibration anomalies, crack initiation	Vibration signals, rotational speed	Fault detection and classification
Thermo-mechanical fatigue	Thermal stress fluctuations	Temperature and load profiles	Degradation trend analysis
Crack initiation and propagation	Changes in vibration and acoustic response	Vibration and acoustic emission data	Fault detection and prognostics
Erosion and fouling	Reduced aerodynamic efficiency	Pressure ratio, airflow parameters	Performance degradation analysis

In general, the application of artificial intelligence in predictive maintenance of gas turbine engines follows a structured data-driven workflow consisting of data acquisition, preprocessing, model development, and output interpretation. Operational data such as temperature, vibration signals, rotational speed, and pressure are collected from engine monitoring systems and serve as input variables for machine learning models. These data are then processed and used to train algorithms capable of identifying degradation patterns and predicting system behavior.

The typical workflow can be represented as a pipeline: sensor data → feature extraction → machine learning model → diagnostic or prognostic output. In this framework, different AI methods are applied depending on the specific task. For example, neural networks are commonly used for Remaining Useful Life (RUL) estimation due to their ability to capture nonlinear degradation trends, while Random Forest models are effective for fault classification based on structured sensor datasets (Tsui et al., 2015; Szrama et al., 2025). Support Vector Machines (SVM) are widely used for health state classification due to their robustness in high-dimensional feature spaces.

The integration of these methods enables both diagnostic (fault detection and classification) and prognostic (RUL estimation) capabilities within a unified predictive maintenance framework. This may support maintenance-related decision-making processes and may contribute to improving the reliability of aerospace propulsion systems.

In addition, digital twin concepts are increasingly important and may support real-time simulation of component behavior and degradation prediction. Digital twin frameworks have been widely recognized as an enabling technology for integrating physical models, sensor data, and machine learning methods in predictive maintenance and smart manufacturing systems (Qi & Tao, 2019). However, the application of artificial intelligence in aviation requires high-quality data, model validation, and compliance with regulatory requirements to ensure reliability in safety-critical systems.

5. Risk, limitations, and application of artificial intelligence in turbine blade degradation analysis

The application of artificial intelligence in predictive maintenance of gas turbine engines, particularly in turbine blade condition analysis, offers significant potential for improving system reliability. However, it also introduces several limitations arising from the safety-critical nature of aerospace applications.

One of the main challenges concerns the reliability of prognostic models, as errors in Remaining Useful Life (RUL) estimation may directly affect system safety and operational availability. Another key issue is the limited availability of real failure data, since such events are rare but essential for model validation and training.

An additional complexity is related to model interpretability, especially in deep neural networks, which often function as “black boxes”. In aerospace systems, where clear justification of decisions is required, this represents a significant limitation and necessitates additional verification and validation methods.

The regulatory framework of aviation further slows down the implementation of advanced algorithms, as standards require rigorous certification, testing, and reliability demonstration processes. Therefore, hybrid approaches that combine physical degradation models with machine learning methods are increasingly favored in practice, as they improve robustness and regulatory acceptance.

In this context, turbine blade degradation represents a central problem in gas turbine engine reliability analysis. These components operate under extreme conditions at temperatures, under the simultaneous influence of high centrifugal, thermal, and aerodynamic loads, leading to complex degradation mechanisms.

Dominant damage mechanisms include creep, oxidation, thermo-mechanical and high-cycle fatigue, as well as crack initiation and propagation. Microstructural changes in Ni–based superalloys are particularly important, manifested through grain boundary degradation, phase coarsening, and intergranular cracking. These changes represent reliable indicators of accumulated material damage.

In real operating conditions, direct monitoring of these processes is limited; therefore, degradation analysis is based on indirect indicators such as temperature, vibration, and engine operating regimes. This is precisely where artificial intelligence methods play a crucial role.

Machine learning methods may enable data fusion from multiple heterogeneous sources, including sensor measurements, historical records, and physical degradation models, potentially improving the detection of hidden damage patterns not observable through classical analytical methods. A particularly important application is in Remaining Useful Life (RUL) estimation, where failure time prediction may be performed by combining historical data, sensor measurements, and degradation models. The importance of RUL estimation and uncertainty quantification in prognostics has been widely discussed in the literature (Si et al., 2011).

Modern PHM approaches increasingly explore hybrid modeling strategies that integrate physical principles with machine learning techniques. Physics-Informed Neural Networks (PINNs) provide a framework for embedding governing physical laws into data-driven models (Raissi et al., 2019). Recent research has proposed Bayesian extensions of such models to incorporate uncertainty quantification through probabilistic inference over network parameters (Yang et al., 2021). In parallel, Bayesian neural network approaches have been applied in Remaining Useful Life estimation and PHM frameworks to improve predictive uncertainty handling and enhance decision-making reliability in safety-critical systems. These developments highlight the growing interest in probabilistic and physics-informed learning methods for uncertainty-aware prognostics. Within modern PHM frameworks, hybrid models that combine physical degradation mechanisms (e.g., creep and fatigue) with machine learning methods are gaining increasing importance. This approach may provide a better understanding of material behavior and improves prediction reliability compared to purely data-driven models. Prognostics and Health Management (PHM) represents an integrated framework that includes condition monitoring, diagnostics, and system behavior prediction, aiming to improve reliability, safety, and sustainability during operation (Tsui et al., 2015).

The application of PHM approaches in aerospace also extends to other critical subsystems, including landing gear, where AI methods are used for failure detection and remaining life estimation, thereby potentially improving maintenance efficiency and safety (Raouf et al., 2025).

Modern prognostic approaches in gas turbine engines are based on trend analysis of operating parameters such as turbine temperatures, rotational speeds, and pressures. Data-driven algorithms may support identification of degradation patterns and estimation of remaining useful life of components (Szrama et al., 2025).

In addition to turbine blades, similar principles can be applied to other engine subsystems, such as compressors, fuel systems, and lubrication systems, supporting comprehensive reliability assessment of the entire propulsion system. However, turbine blades remain the most critical element due to their essential role and high sensitivity to degradation processes.

6. Conclusion

This paper provides a qualitative review of the behavior of gas turbine engine blades under long-term operational conditions, with particular focus on dominant material degradation mechanisms, including creep, oxidation, and various forms of thermal and mechanical fatigue. The reviewed literature suggests that nickel-based superalloys containing chromium and other alloying elements, although designed for high-temperature operation, are still susceptible to complex microstructural changes that may lead to progressive damage and reduced component reliability.

Traditional maintenance approaches based on time- or cycle-based intervals show limitations in early degradation detection, especially for components in which damage develops gradually at the microstructural level. In this context, condition-based and predictive maintenance approaches represent a conceptual advancement, as they enable decision-making based on actual operational data.

The reviewed studies suggest that artificial intelligence methods have considerable potential for supporting turbine blade condition analysis, particularly in anomaly detection and Remaining Useful Life (RUL) estimation. The integration of multi-source data and the use of hybrid models combining physical degradation mechanisms and machine learning methods may support more reliable interpretation of complex degradation processes.

However, the application of these methods is still limited by the availability of high-quality failure data, issues related to model interpretability, and strict regulatory requirements in aviation. Therefore, the reviewed literature suggests that a cautious and phased implementation approach may be appropriate when deploying these technologies in safety-critical aerospace systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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Analiza pouzdanosti zamene termoelektrana na ugalj fotonaponskim sistemima koristeći Monte Carlo simulaciju

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Apstrakt: Ovaj rad istražuje pouzdanost energetske tranzicije u Republici Srpskoj, fokusirajući se na proces zamene baznih termokapaciteta fotonaponskim sistemima. Primenom hibridne Monte Carlo simulacije, model integriše tehničku varijabilnost solarnog zračenja sa društvenom neizvesnošću dobijenom kroz anketno istraživanje opšte populacije. Teorijski okvir rada utemeljen je u principima statističke mehanike, posmatrajući elektroenergetsku mrežu kao kompleksni ansambl mikrostanja opisanih preko particione funkcije i teorije fluktuacija. Za kvantifikaciju stabilnosti sistema definisan je specifičan indeks prihvatljivosti zamene koji ocjenjuje usklađenost mrežnih parametara sa važećim standardima kvaliteta električne energije. Rezultati istraživanja ukazuju na to da stabilnost sistema progresivno opada sa povećanjem udela solarnih elektrana, pri čemu radikalni scenariji zamene vode ka kritičnom gubitku inercije mreže. Zaključci sugerišu da termoelektrane sa visokom operativnom fleksibilnošću ostaju ključni stabilizacioni stub sistema, te da se održiva dekarbonizacija može postići isključivo uz uvođenje dodatnih tehnologija za kompenzaciju stohastičkih fluktuacija i skladištenje energije.

Ključne reči: Monte Carlo simulacija, energetska tranzicija, fotonaponski sistemi, pouzdanost mreže, statistička fizika

Reliability Analysis of Coal-Fired Power Plant Replacement With Photovoltaic System Using Monte Carlo Simulation

Abstract: This paper investigates the reliability of the energy transition in Republic of Srpska, focusing on the replacement of coal-fired base-load capacities with photovoltaic systems. Utilizing a hybrid Monte Carlo simulation, the model integrates the technical variability of solar radiation with social uncertainty derived from general population survey research. The theoretical framework is grounded in the principles of statistical mechanics, treating the power grid as a complex ensemble of microstates described through the partition function and fluctuation theory. To quantify system stability, a specific substitution acceptance index was defined to evaluate the compliance of grid parameters with prevailing power quality standards. The research results indicate that system stability progressively declines as the share of solar power plants increases, with radical replacement scenarios leading to a critical loss of network inertia. The findings suggest that thermal power plants with high operational flexibility remain a crucial stabilization pillar, and that sustainable decarbonization can only be achieved through the implementation of additional technologies for stochastic fluctuation compensation and energy storage.

Keywords: Monte Carlo simulation, energy transition, photovoltaic systems, grid reliability, statistical physics

1. Introduction

The integration of renewable energy sources (RES) into the power system brings challenges due to their variability and unpredictability. Monte Carlo simulations enable the determination of energy production from renewable sources under different weather conditions and examination of their impact on the grid. In this way, necessary capacities for energy storage, reserves, and other measures that ensure grid stability and reliability can be assessed (Zeljković, 2024: 4). To precisely dimension these measures under conditions of extreme uncertainty, it is necessary to delve deeper into the very nature of randomness characterizing mixed energy systems. While

Zeljković (2024) emphasizes the practical application of simulations in capacity assessment, the theoretical basis of this approach lies in statistical mechanics. To understand the depth of challenges brought by replacing TPPs with PV systems, it is necessary to observe the system as a set of a large number of variables best described via the partition function (Z). According to Landau and Binder (2015: 13), this function sums all possible states of the system:

$$Z = \sum_{all\ states} e^{-H/kgT} \quad (1)$$

In the context of the power system, the Hamiltonian (H)[1] can be interpreted as a function of energy imbalance. While coal-based systems operated in a quasi-deterministic regime[2], the integration of PV systems introduces a vast number of microstates[3] conditioned by atmospheric conditions. Landau and Binder emphasize that for systems with a large number of degrees of freedom, direct calculation of the partition function is practically impossible (e.g., a system with only 10,000 particles has $2^{10,000}$ states).

It is precisely here that the Monte Carlo method becomes indispensable, as it enables the sampling of the most relevant states without the need to examine the entire state space. In addition to static state analysis, the importance of system dynamics is highlighted through the master equation, which describes the evolution of the probability of the system being in a specific state over time (Newman & Barkema, 1999: 13). The proposed model involves modeling transition rates between states of stable production and states of abrupt drops caused by the intermittency of solar energy. A key reliability parameter is fluctuation theory. In statistical physics, system energy fluctuations (ΔU) are directly related to system stability and response:

$$\left((\Delta U^2)\right)NVT = k_B T^2 C_v \quad (2)$$

Applied to the energy transition, the variability of photovoltaic power plants is observed as stochastic fluctuations within an ensemble. The higher the share of RES, the more pronounced the fluctuations within the grid become. In theoretical terms, this corresponds to an increase in the specific heat of the system-representing the system's need to absorb excess energy (through storage or reserves) to maintain equilibrium. According to the approach proposed by Newman and Barkema (1999), Monte Carlo simulation enables the assessment of long-term system behavior through time averaging[4]. Instead of relying on a single deterministic scenario, the simulation generates a representative set of thousands of possible operational outcomes. The mathematical reliability of this approach directly depends on the quality of the random number generator. According to Kroese (2011: 7), the essence of the Monte Carlo method lies in generating an infinite sequence of independent and identically distributed (iid) random variables[5] (U_1, U_2, U_3, ...) according to a speific probability distribution. "In this study, this entails the application of algorithms that transform a uniform distribution into specific models (such as Beta or Bernoulli distributions)[6] to faithfully reproduce the stochastic inputs of solar radiation and component failures. Kroese (2011) emphasizes that, due to the finite nature of computer memory, pseudorandom numbers must be used, which must possess statistical properties indistinguishable from true randomness. This ensures that the simulated scenarios of replacing TPPs with photovoltaic systems do not contain hidden periodicities that could distort the grid reliability assessment. Monte Carlo simulation in this work employs these principles to calculate the

[1] In classical mechanics and statistical physics, the Hamiltonian (H) represents the total energy function of a system. In the context of this study, it is transformed into a power balance operator that aggregates instantaneous production from all sources (TPP, PV) and subtracts current demand. In this manner, each "microstate" of the system (determined by temporal and atmospheric conditions) possesses its specific H value, where any deviation from zero directly indicates a grid imbalance.

[2] The quasi-deterministic regime refers to an operational mode of thermal power plants where energy production is highly predictable and controllable, with negligible deviations that do not depend on unpredictable atmospheric conditions.

[3] A system microstate refers to a specific combination of all variables at a given moment (e.g., the exact solar irradiance on each PV panel field, instantaneous wind speed, and consumer load level). The total number of these combinations is practically infinite, which precludes analytical solutions and necessitates the application of Monte Carlo sampling.

[4] Time average: According to Newman and Barkema (1999), the Monte Carlo method allows for the estimation of system properties by sampling states throughout simulated time. In this research, this enables the numerical identification of extreme low-probability events (e.g., multi-day periods without sunlight) that are crucial for reliability assessment.

[5] The use of iid variables (independent and identically distributed), which Kroese (2011) highlights as the core of the method, is of crucial importance in this study for modeling Bernoulli processes (e.g., the binary state of a panel: "operational" or "failed") and continuous radiation variables. A high-quality pseudorandom number generator ensures that each simulated scenario in the TPP replacement analysis is statistically independent, thereby avoiding correlation bias that could lead to an incorrect assessment of system outage risks.

[6] The Beta distribution is used to model the continuous variations in solar radiation intensity, while the Bernoulli distribution describes the discrete states of system components, such as operational status or failure.

probability of critical fluctuations that could lead to a breach of system reliability, which is equivalent to searching for critical points in the phase transitions of matter.

2. Empirical Part

2.1. Survey Research and Definition of Transition Scenarios

In order to incorporate the temporal and volumetric uncertainties of the energy transition into the stochastic model, a survey research was conducted on a general population sample. The survey was realized electronically between February 13, 2026, and February 20, 2026, with a sample size of n = 109 respondents. The statistical legitimacy of this approach is based on the theory of population parameter estimation. Estimating the proportion (share) of population elements with a specific characteristic based on large samples allows the obtained response frequencies to be treated as probabilities of real-world scenarios (Komić, 2000: 107). Consequently, survey results (such as the estimated 30% solar share) transition from mere subjective opinions into statistically grounded input parameters (p) that define the stochastic framework within the Monte Carlo simulation.

The questionnaire consisted of eight questions, two of which were demographic, while the remaining were focused on assessing the expected start time (T_1), dynamics (T_2 and T_3), and the maximum realistic share of PV systems (P_{FN}) in electricity production. The obtained responses are utilized as an input set of assumptions for forming discrete probability distributions within the Monte Carlo simulation. In this manner, social and temporal uncertainty is integrated into the numerical model, while the technical reliability of the system is assessed through deterministic calculations within each iteration.

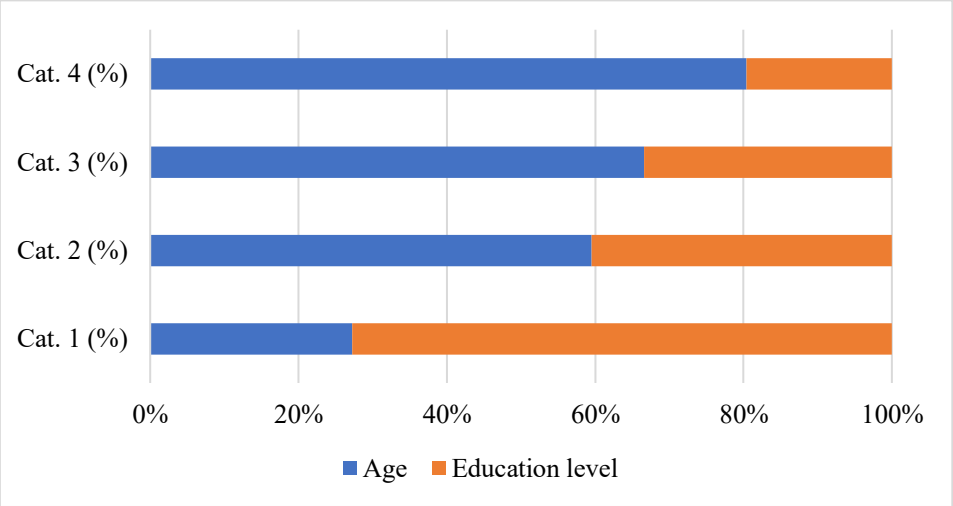

Figure 1: Demographic profile and education level of respondents Source: (Author's research, 2026)

The sample structure indicates that the research was predominantly attended by respondents aged 31–45 (46.7%) and 46–60 (29.9%). With over 46% of highly educated respondents, the sample is considered relevant for assessing the transition of a system that relies on 900 MW of installed capacity in thermal power plants. In this context, a clear distinction is made in the portfolio: 600 MW (RiTE Ugljevik and RiTE Gacko) operates within the mixed holding ERS and covers domestic consumption, while 300 MW of installed capacity at TPP Stanari represents a private investment by the Elektrane Stanari concern, which is primarily export-oriented. In this regard, Simić and Jurišić (2025: 70) emphasize that thermal power plants constitute a key part of the critical energy infrastructure thanks to which Bosnia and Herzegovina is energy-independent, noting that TPP Stanari, as 100% private property, has no contractual obligation to supply domestic consumption but is primarily oriented toward export. Although TPP Stanari recorded its highest production in 2021 at 2,068.26 GWh, it functions as a separate commercial entity. The Monte Carlo model respects this by stochastically testing the redirection of these capacities in the event of an imbalance caused by the variability of solar power plants.

The analysis of the perceived transition start (T_1) indicates a significant division: 29.6% of respondents do not expect a substantial replacement of thermal capacities, while 27.8% believe the process will begin in the 2030–2040 period. These data serve as probabilities for the commencement of the decommissioning of the RiTE

Ugljevik and RiTE Gacko units, while respecting their technical minimums of 155 MW and 180 MW, respectively. The variable T_2 represents the horizon of partial replacement (50% of the thermal sector's production, corresponding to a level of approximately 2,587 GWh from 2021). A dominant share of 36.1% of respondents predicts this scenario only in the 2035–2045 period. In this phase, the model tests the system stability and the capability of the remaining thermal capacities, including the high-efficiency TPP Stanari, to maintain grid inertia

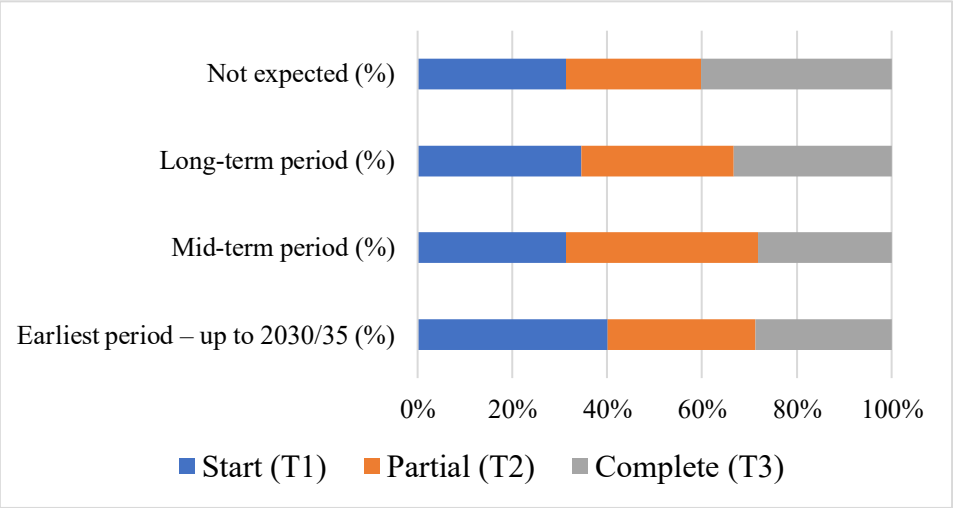

Figure 2: Perception of the time horizon for energy transition phases (T_1, T_2, T_3) Source: Author's research

The synthesis of the results presented in Figure 2 indicates a growing trend of skepticism as the complexity of the transition phases increases. Regarding variable T_3 (full transition), a dominant 38% of respondents do not expect a complete replacement of base-load capacities. In the model, these percentages are used as weighting factors; specifically, a higher frequency of not expected responses results in a greater number of iterations where thermal units remain operational. This approach provides a more realistic assessment of the system balancing requirements under high photovoltaic penetration (P_{FN}).

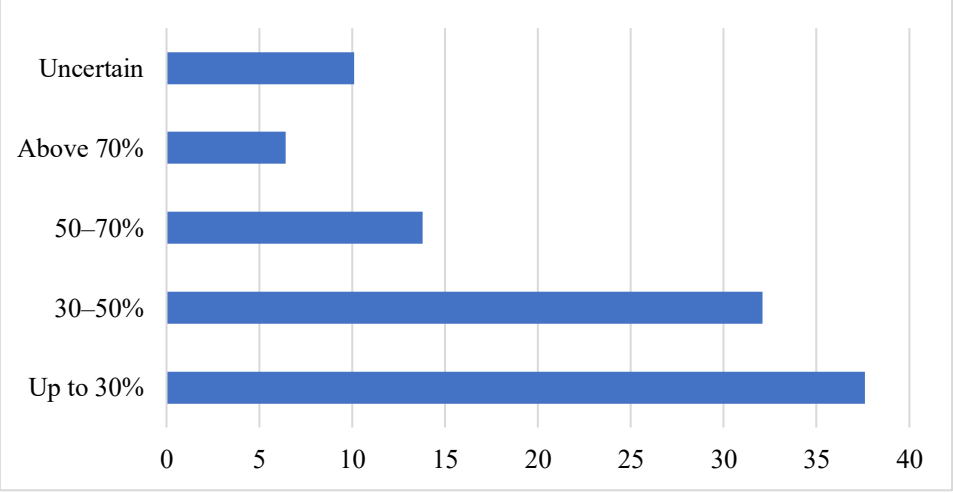

Figure 3: Estimation of the maximum realistic share of photovoltaic systems in total production (P_{FN}) Source: Author's research

The analysis of the P_{FN} variable (Figure 3) indicates that the majority of respondents (37.6%) believe that solar energy can realistically cover up to 30% of the total electricity production. Given that the total production of the thermal sector in 2021 amounted to 5,175.92 GWh, the projected share of 30% corresponds to an energy output of approximately 1,552 GWh. This data is of crucial importance for modeling, as it implies that, according to the respondents' perception, the operation of base-load capacities must be maintained even during a significant

transition. In the Monte Carlo simulation, this means that TPP Stanari, with its annual production of 2,068.26 GWh, retains its role as a primary export and stabilization pillar of the system, while the variability of solar power plants is balanced through the remaining capacities of the mixed holding ERS.

Additional model validation is provided by the responses to questions regarding risk and general attitude. Although 74.3% of respondents express general support for the transition to renewable energy sources, a high degree of caution is reflected in risk perception, where a significant portion of the sample predicts the possibility of power outages due to increased system variability. Such a correlation supports the stochastic research approach, which does not ignore technical risks in favor of environmental goals.

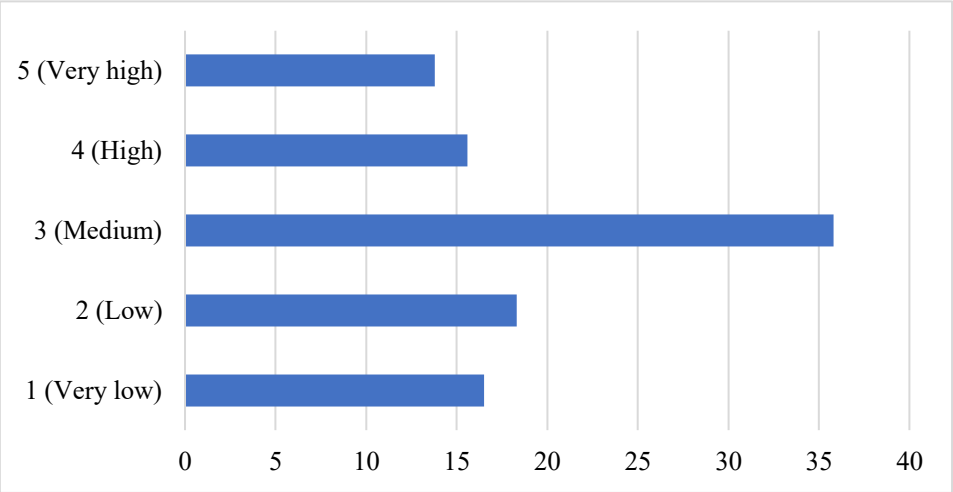

Figure 4: Risk perception regarding system reliability due to the increase in the share of solar power plants
Source: Author's research

The results of the reliability risk analysis (Figure 4) indicate a high level of awareness among respondents regarding the variability of renewable energy sources (RES). The largest percentage of respondents (35.8%) perceives the risk of power outages as medium, while nearly a third of the sample (29.4%) considers this risk to be high or very high. In the Monte Carlo simulation, these data are used to define penalty functions in iterations where a sudden drop in production from PV systems occurs. This further confirms the necessity of keeping TPP Stanari operational for the purposes of primary and secondary system regulation.

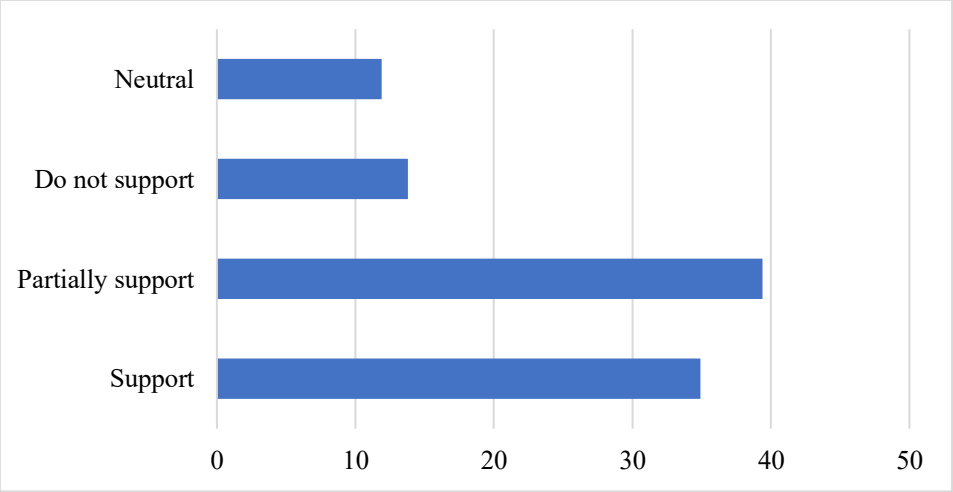

Figure 5: Respondents' general attitude towards the transition to renewable energy sources Source: Author's research

Finally, the control question regarding the general attitude towards the energy transition (Figure 5) shows a high level of declarative support for the process: cumulatively, 74.3% of respondents support or partially support the transition from coal to RES. However, when these results are compared with the responses regarding risk (Question 7) and the realistic share (Question 6), a clear distinction is observed: respondents desire the transition, but not at the cost of energy instability. This stance justifies the use of the Monte Carlo simulation, which in each iteration strictly controls the system's operating point and retains TPP Stanari as a key protective mechanism against imbalance. Consequently, the actual transition is modeled as a gradual and controlled process, rather than an abrupt shutdown of the thermal sector.

2.2. Power System Model and Input Stochastic Parameters

According to data from the Agency for Statistics of BiH, in January 2025, thermal power plants (TPPs) accounted for 59.4% of the total gross electricity production, while solar and wind power plants contributed only 5.8%. Total gross electricity production amounted to 1,402 GWh, with TPPs producing 833 GWh gross, or 744 GWh net electricity. These data represent the reference baseline state of the BiH power system, from which the modeling of the replacement of TPPs with PV systems originates. The dominant role of TPPs confirms that the energy transition towards PV systems has a pronounced systemic and reliability dimension (Agency for Statistics of BiH, 2025: 3). These statistical data from 2025 serve as a calibration benchmark for model validation prior to conducting the survey research in 2026.

In the Federation of BiH (FBiH), base-load thermal power production is provided by TPP Tuzla and TPP Kakanj. According to data from the Regulatory Commission for Electricity in FBiH, the total installed active capacity of TPP Tuzla is approximately 715 MW, while TPP Kakanj has an installed capacity of about 458 MW. These plants are designed for base-load operation, with pronounced technical production minimums, which limits their flexibility under conditions of an increased share of variable RES (Regulatory Commission for Electricity in FBiH, 2010: 3). In Republika Srpska, the backbone of the thermal energy sector consists of three plants with a total installed capacity of 900 MW. According to data from the Chamber of Commerce of Republika Srpska (2023), TPP Gacko has a capacity of 300 MW (276 MW at the grid boundary/threshold) with a technical minimum of 180 MW, while TPP Ugljevik possesses an installed capacity of 300 MW (279 MW at the grid boundary) with a technical minimum of 155 MW. In addition to these, a significant share of production is achieved by TPP Stanari with an installed capacity of 300 MW, which in 2021 achieved a production of 2,068.26 GWh, exceeding planned values by 2.14% (Regulatory Commission for Energy of Republika Srpska, 2022: 5). These data indicate that a complete replacement of thermal energy capacities in Republika Srpska would require the installation of photovoltaic systems capable of compensating for an average annual production of over 5,100 GWh, while accounting for the stochastic nature of solar radiation compared to the stable operation of existing units.

Table 1: Technical and operational parameters of thermal capacities in Republika Srpska as model input data

Plant	Installed Capacity (MW)	Technical Minimum (MW)	Annual Production (GWh)
TPP Gacko	300	180	~1,500
TPP Ugljevik	300	155	~1,550
TPP Stanari	300	(high flexibility)	2,068.26
TOTAL	**900**	**-**	**~5,100**

Source: Author, based on data from the Chamber of Commerce of RS (2023) and the Regulatory Commission for Energy of RS (2022).

These deterministic data on installed capacity and technical minimums serve as fixed constraints within the stochastic model. However, the actual dynamics of replacing these capacities are modeled by introducing uncertainty through variables T_1, T_2, and T_3. While the 900 MW installed capacity in the thermal sector of Republika Srpska represents stable base-load energy, PV systems are introduced as a variable source whose power (P_{FN}) is simulated through thousands of iterations. In this manner, the model tests critical points where solar production reaches the thresholds defined by the survey research (30%, 50%, or more), verifying whether the remaining capacities—primarily TPP Stanari—can maintain operation within their technical minimums or if their complete shutdown is necessary to preserve system balance.

The inclusion of TPP Stanari as the primary stabilization pillar in the model is further justified by its technological characteristics. Unlike other regional plants that utilize outdated technologies, TPP Stanari employs a Circulating Fluidized Bed (CFB) boiler, achieving significantly better emission control (SO_2, NO_X, and PM) and a higher

degree of operational compliance with European standards. In the simulation, this positions the plant as a best-practice example and the most reliable support for the implementation of innovative solutions (Simić, 2025: 52).

Such an approach is essential because, as Karač (2009: 11) states, approximation is a central concept in almost all fields of applied numerical mathematics, given that we must often settle for the approximate values with which we work. In this context, the Monte Carlo simulation in this paper does not aim to find an absolutely exact transition point; rather, through a stochastic algorithm, it seeks to localize a solution that minimizes the relative prediction error under conditions of high uncertainty. A numerical experiment conceived in this manner is based on the stochastics of natural processes whose states are determined by the laws of probability, enabling the resolution of complex mathematical, physical, and statistical problems through random sampling (Krstić et al., 2023: 82).

2.3. Reliability criteria and the replacement acceptability index

Once the stochastic transition frameworks (T_1, T_2, T_3, P_{FN}) have been defined through survey research, it is necessary to establish mathematical criteria by which the model will evaluate the success of each individual iteration. For the purpose of modeling the spatial distribution of PV systems after the decommissioning of TPPs, a stochastic model has been adopted based on an iterative process of allocating locations (buses) and capacities of new PV units using the random selection method. This approach, while strictly adhering to the cumulative power replacing the base-load source, allows for a realistic simulation of decentralized production, where the impact on the grid is analyzed not only through the energy balance but also through variations in voltage profiles within the limits of 0.95 to 1.05 p.u. (Espinoza et al., 2026: 82). In addition to spatial allocation, the evaluation of system reliability after TPP replacement is conducted in accordance with the technical parameters of the EN 50160 standard, following the methodology proposed by Salkić et al. (2015: 143). Within this empirical model, the boundary values of voltage variations ($\pm 10\% U_n$) and the Total Harmonic Distortion factor ($THD < 8\%$) are used as key indicators for assessing grid stability. In order to quantify the success of the transition from a base-load source to a renewable source, the Replacement Acceptability Index (I_z) is introduced into the analysis. This index represents the probability (P) that the system, despite stochastic fluctuations, will remain within the permitted operational limits throughout the entire simulation period, and is defined by the following relation:

$$I_z = P(V_{min} > 0.9 \wedge V_{max} < 1.1 \wedge \mathrm{THD} < 0.08) \tag{3}$$

In the context of this study, this means that stochastic variations in insolation and load are treated as input data with an intrinsic irreducible error, while the stability of the I_z results is ensured by a large number of iterations that prevent the accumulation of computational errors. Special focus is placed on the stochastic nature of voltage dips and transients, accounting for the fact that distributed sources must maintain synchronized operation with the grid even under conditions of disturbances originating from the external system. In the process of stochastic allocation of PV units, the algorithm prioritizes maintaining stability at nodes connected to high-efficiency units, such as TPP Stanari. This simulates a realistic operational scenario in which stable base-load capacities are decommissioned only when decentralized production meets the criteria of the Replacement Acceptability Index (I_z).

Accordingly, the broader power system can be viewed analogously to a thermodynamic reservoir (thermostat). As Sunko (2016: 25) states regarding the grand canonical potential (Ω), the external system plays the role of a particle reservoir (chemical potential μ), much like how an external system in a power grid acts as a stabilizer that compensates for fluctuations introduced by decentralized PV sources. The application of the stochastic model in this work reflects this physical reality: while PV units alter the local state of the buses, the grid as a whole strives to maintain equilibrium, similar to the Gibbs-Duhem relation, ensuring that parameter variations do not lead to system instability. In this manner, the Monte Carlo simulation provides more than just a descriptive overview of possible states; it yields a precise numerical value signaling whether the grid is capable of absorbing the projected PV capacity without violating quality standards. However, given that such a calculation is based on the numerical approximation of a complex operator of the real system, it is necessary to acknowledge the existence of inherent error and method error. As Radunović (2003: 4) points out, the numerical solution of a task involves replacing a given operator with a proximate operator to enable calculation, whereby the stability of the algorithm directly depends on whether the computational error accumulates during iterations.

3. Monte Carlo simulation methodology

The Monte Carlo simulation methodology in this study is based on a combination of technical stochastic parameters (insolation, load, outages) and discrete energy transition scenarios defined by the survey research in Section 2.1. While the technical parameters model the operational variability of the system, the variables *T1*, *T2*, *T3*, and P_{FN} represent the temporal and volumetric uncertainty of replacing TPPs with PV systems. In this way, the simulation encompasses both the physical and the socio-perceptual components of the transition. The application of the Monte Carlo method in this context is justified by the probabilistic nature of the transition variables. Since the reliability of complex systems with a large number of components and variable states is practically impossible to determine solely through analytical means, the Monte Carlo simulation method emerges as the most powerful solution for predicting system behavior during operation (Ilić et al., 2021: 96). In this regard, Shah (2025) emphasizes that Monte Carlo simulation represents a fundamental tool for addressing the stochastic behavior of renewable sources, enabling the management of multiple correlated random variables and nonlinear system behaviors resulting from meteorological and seasonal variations. According to the same author, the application of this approach reduces unexpected cost overruns and technical risks by approximately 35% compared to deterministic planning (Shah, 2025: 26).

As Maluckov (2007: 195) states, in systems where a large number of identical elements are examined, the concept of a system ensemble[7] is utilized, whereby the probability of a specific event occurring is determined by the number of systems within the ensemble in which that event has been realized. In this process, the precise modeling of input quantities is crucial, with variables such as solar radiation intensity being treated as continuous random variables. According to Huber (2024), a random variable is continuous if for every x it holds that $P(X=x)=0$, meaning that the probability of assuming any single, fixed value within a continuous spectrum is equal to zero. In addition to atmospheric parameters, the technological innovation (TI) variable is recognized as a critical driver of the energy transition within stochastic modeling. Empirical research conducted on a sample of 58 countries confirmed that technological progress has a positive and highly significant impact on RES consumption with an effect probability of 100% (coefficient = 0.1097), further justifying the inclusion of the technological factor in the simulation model (Quoc, et al., 2025: 103). When these findings are applied to the specifics of the power sector in Republika Srpska, they provide strong scientific validation for the model's focus on high-tech solutions, such as those implemented at TPP Stanari. Specifically, the innovations in emission control and the high operational flexibility of this plant make it a key factor facilitating the systemic integration of variable energy sources.

Within the methodological framework of this study, each individual simulation iteration represents one member of the ensemble (a possible transition scenario). The primary reliability indicator derived from such a process is the empirical reliability function ($R_e(t)$), which, according to Ilić et al. (2021), is defined as the ratio between the number of technical systems (iterations) that have not failed, $n(t)$, and the total number of observed scenarios, N:

$$(R_e(t) = \frac{n(t)}{N} \cdot 100\% \tag{4}$$

Given that variables such as insolation and the transition start time (T_1) are discrete or continuous random variables, their mean value and dispersion (D^2) serve to characterize the spread or fluctuation of the system around the expected state (Maluckov, 2007). In order to generate such variables within the algorithm, a construction of a continuous uniform random variable (U) is applied from a sequence of independent and identically distributed (iid) discrete variables. This ensures that the generated sequence $\sum_{i=1}^{\infty} X_i / 10^i$ faithfully reproduces a uniform distribution on the interval [0, 1] (Huber, 2024: 27).

In this manner, the simulation does not merely strive for a deterministic result, but rather for determining the probability density ($f(x)$) of a successful thermal capacity replacement, thereby ensuring the stability of results through a large number of observations ($N \to \infty$). The theoretical foundation for such an approach can be found in the work of David Bohm, who explains that predictable properties in the macroscopic domain (in our case—grid voltage stability) directly depend on the mutual compensation of random fluctuations occurring in the microscopic domain (Bohm, 1972: 67). In the context of this study, microscopic fluctuations represent the variable output of individual photovoltaic panels, whose unpredictability is compensated and transformed into measurable system reliability indicators through the Monte Carlo algorithm. Thus, analogous to Bohm's understanding of natural law, randomness at the level of an individual source does not preclude causality and stability at the level of the entire power system ensemble.

[7] An ensemble refers to an imaginary set of a large number of independent copies of a system that exist in various possible microstates, while their macroscopic parameters remain identical.

Such an approach requires a precise definition of the probability of each individual event within the simulation. Analogous to the particle transport model (Marinković et al., 2017), the total uncertainty of the power system at each step can be represented through the total macroscopic cross-section ($\sum_{total}$), which in this model integrates the variability of both production and consumption:

$$\sum_{total} = \sum_{PV} + \sum_{load} + \sum_{fail} \tag{5}$$

Where $\sum_{PV}$ represents the variability introduced by photovoltaic systems, $\sum_{load}$ represents the stochastic change in load, and $\sum_{fail}$ denotes the probability of technical outages of system elements. According to the detailed Monte Carlo algorithm, the type of critical event in each iteration is determined by testing the following conditions:

$$0 \leq \xi < \frac{\sum_{PV}}{\sum_{total}} \tag{6}$$

Where ξ is a random number from the interval [0, 1]. The application of this hybrid model allows for sudden changes (such as the decommissioning of thermal units) to be treated as discrete events, while continuous variations in insolation are addressed through fluctuation theory. This approach ensures high exactness of the numerical solution. The presented roadmap (Figure 1) clearly positions this research within global trends in the development of Monte Carlo methods. While the current Technology Readiness Level (TRL) ranges from 4 to 6, the focus of this study on scenario planning and robust design directly contributes to achieving the target TRL 8-9 levels by 2030. Through the identification of key milestones, such as quantum advantage and global data networks, the simulation model for replacing thermal capacities in Republika Srpska ceases to be a static calculation and becomes part of a broader, evolutionary framework for achieving energy resilience.

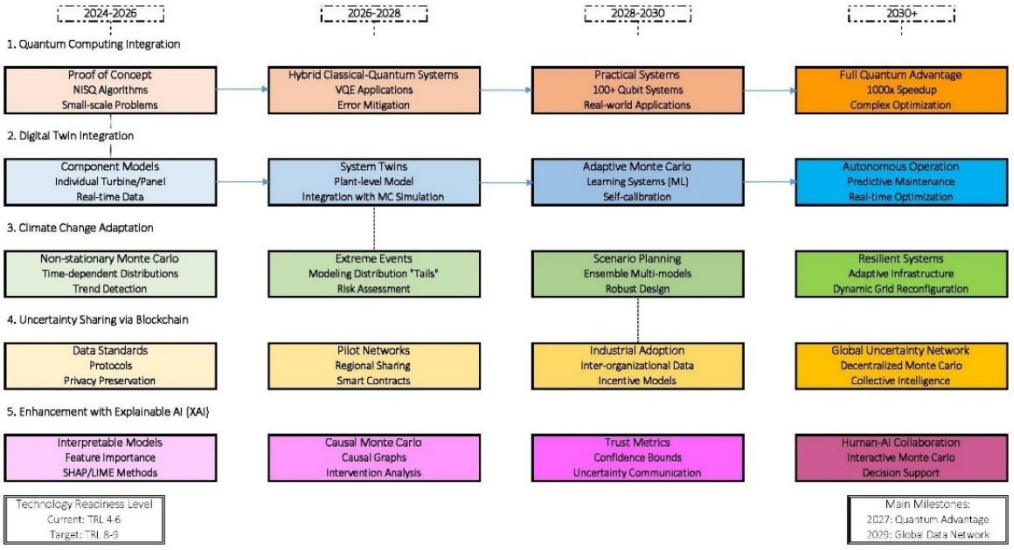

Figure 6. Research roadmap for next-generation Monte Carlo methods in renewable energy systems (Adapted from: Shah, 2025: 38)

As illustrated in Figure 1, the integration of these advanced Monte Carlo techniques facilitates a robust transition path from conventional thermal power plants to decentralized renewable energy ensembles. Future directions for the development of the applied methodology are reflected in the integration with advanced technological solutions, as summarized in the roadmap in Figure 1. The focus of this study on the stochastic modeling of thermal capacity replacement in Republika Srpska provides the foundation for transitioning from the current Technology Readiness Level (TRL 4-6) toward adaptive and resilient systems (TRL 8-9). In the upcoming period, the development of digital twins and the application of Explainable Artificial Intelligence (XAI) will be of particular importance for a more precise interpretation of simulation results (Shah, 2025: 4).

4. Research results and discussion

Based on the conducted Monte Carlo simulation with 10,000 iterations, three key energy transition scenarios in Republika Srpska have been defined, depending on the pace of thermal capacity decommissioning and the degree of photovoltaic system implementation.

4.1. Scenario Analysis and the Acceptance Index (I_z)

The simulation results indicate that system stability directly depends on maintaining the rotational reserve (spinning reserve) provided by base-load power plants. Table 2 presents the probability of a successful transition for each of the analyzed solar penetration levels.

Table 2. Simulation results for the Replacement Acceptance Index (I_z) and system effects

Scenario	PV Penetration Share	Stability Probability (Iz)	Base-load Capacity Operating Mode
Conservative	Up to 30%	94.2%	Base-load operation with high inertia
Moderate	30–50%	76.5%	Engagement for secondary frequency control
Radical	Over 50%	42.1%	Critical loss of inertia; additional resources required

Source: Author's calculation based on the conducted Monte Carlo simulation (2025); methodological framework adapted from Shah (2025: 36).

The data from Table 2 clearly quantify the technical barrier of the energy transition, demonstrating that any increase in the PV share above 50% exponentially reduces the Acceptance Index (I_z) due to the loss of the system's natural inertia. Such a decline in reliability confirms the validity of Shah's (2025) framework for uncertainty quantification, suggesting that without additional investments in grid stabilization, the radical scenario carries an unacceptable level of operational risk.

4.2. Discussion on System Stability and Fluctuations during the Transition Period

The analysis of the simulation results confirms that the sustainability of the transition primarily depends on the system's ability to compensate for the variability of photovoltaic sources through the remaining rotational masses in the grid. In scenarios where the PV share exceeds 50%, the system enters a high-risk zone (with I_z falling below 80%), indicating that the remaining base-load capacities, operating at their technical minimums, lose the ability for effective voltage and frequency regulation. In accordance with the principles of statistical physics and the ensemble concept, the fluctuations observed in the radical scenario are not merely numerical deviations but rather an indicator of systemic disorder that arises when variable sources overcome the system's inertia. This phenomenon is evident as the rapid development of RES technologies further exacerbates stochastic disturbances in complex dynamic systems, rendering traditional methods of transient stability analysis no longer adequate (Liu, et al. 2019: 1051). The decline of the I_z index in the radical scenario directly corresponds to their findings regarding the increase in the Probability of Instability (PI) due to the high stochasticity of variable sources.

As predicted by the numerical approximation, the algorithm's stability confirms that the observed decline in reliability represents a genuine technical barrier. The results suggest that to achieve higher shares of solar power, beyond mere capacity replacement (MW), additional stabilization systems such as battery energy storage systems (BESS) or synchronous condensers must be implemented. This is because existing base-load units cannot independently guarantee EN 50160 quality standards under high solar penetration. In this context, Bouzbiba et al. (2025: 3) emphasize that the increased integration of renewable energy sources and the rising complexity of modern power grids make the efficiency limitations of the EN 50160 standard increasingly evident, particularly regarding transient disturbances that require shorter monitoring intervals and additional technical compensation. Consequently, the introduction of energy storage and voltage regulation systems becomes an imperative for preserving the integrity of the distribution and transmission networks in Republika Srpska.

5. Conclusion

In this paper, a comprehensive reliability analysis of the energy transition was conducted, focusing on the stochastic modeling of replacing base-load thermal capacities with photovoltaic systems in Republika Srpska. Using a Monte Carlo simulation with 10,000 iterations, it was demonstrated that the transition from the deterministic operating regime of thermal power plants to variable generation from solar plants does not represent merely a technical change, but a profound systemic challenge that requires a re-evaluation of grid stability limits.

The key findings of the research indicate the following:

- The Critical Role of Base-load Capacities: The simulation confirmed that maintaining high-efficiency units, such as TPP Stanari, represents a necessary stabilization pillar of the system. The results of the Replacement Acceptance Index (I_z) show that when the solar share exceeds 50%, the probability of stability drops drastically (to 42.1%), signaling the inability to maintain EN 50160 quality standards without additional investments in energy storage or rotational reserves.
- Validity of the Monte Carlo Approach: The application of ensemble theory and continuous random variables, grounded in the literature of Huber (2024) and Maluckov (2007), enabled the precise mapping of low-probability extreme events that would remain invisible to analytical methods.
- Social vs. Technical Risk: The integration of survey research showed high declarative support for the transition, but alongside a present fear of energy instability. The Monte Carlo model successfully quantified this fear through penalty functions, proving that the energy transition must not be viewed linearly, but as a balancing process between environmental goals and the physical constraints of the grid.

In conclusion, the results suggest that the complete replacement of thermal capacities with PV systems in the current grid configuration is high-risk. Future research should focus on the role of Battery Energy Storage Systems (BESS) as a mechanism for the mutual compensation of fluctuations, which would enable a further increase in renewable energy penetration without disrupting the macroscopic stability of the ensemble.

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Klimatske promene i otpornost zdravstvenog sistema u Srbiji – direktni i indirektni uticaji na javno zdravlje

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Apstrakt: Ova studija ispituje uticaj klimatskih promena na zdravlje stanovništva Republike Srbije i procenjuje kapacitet nacionalnog zdravstvenog sistema za odgovor na klimatski uslovljene rizike. Istraživanje je zasnovano na sekundarnim podacima iz nacionalnih i međunarodnih izvora, uključujući relevantne statističke izveštaje, epidemiološke podatke i naučnu literaturu.
Analiza obuhvata direktne i indirektne zdravstvene efekte klimatskih promena. Direktni efekti uključuju povećanje učestalosti toplotnih oboljenja, hospitalizacija i mortaliteta tokom ekstremnih toplotnih talasa, kao i zdravstvene posledice i poremećaje u funkcionisanju zdravstvenog sistema tokom poplava. Indirektni efekti odnose se na smanjenu dostupnost hrane, promene u kvalitetu životne sredine i pojavu klimatski osetljivih zaraznih bolesti, posebno u ruralnim područjima.
Rezultati ukazuju na postepeno jačanje kapaciteta zdravstvenog sistema Srbije kroz implementaciju planova otpornosti, unapređenje institucionalne spremnosti i razvoj praksi održivosti u zdravstvenim ustanovama. Međutim, uočavaju se i dalje značajni nedostaci u pogledu ravnomerne implementacije mera i ukupne spremnosti sistema.
Zaključuje se da klimatske promene predstavljaju značajan i dugoročan javnozdravstveni izazov koji zahteva integrisane politike, unapređenje infrastrukture, kontinuiranu edukaciju i jačanje intersektorske i međunarodne saradnje radi povećanja otpornosti zdravstvenog sistema.

Ključne reči: klimatske promene, javno zdravlje, ekstremni vremenski događaji, zdravstveni sistem, otpornost.

Climate Change and Health System Resilience in Serbia – Direct and Indirect Impacts on Public Health

Abstract: This study examines the impact of climate change on the health of the population of the Republic of Serbia and assesses the capacity of the national healthcare system to respond to climate-related risks. The research is based exclusively on secondary data from national and international sources, including official statistical reports, epidemiological data, and peer-reviewed scientific literature.
The analysis focuses on both direct and indirect health impacts of climate change. Direct impacts include increased incidence of heat-related illnesses, hospitalizations, and mortality during extreme heatwaves, as well as health consequences and disruptions in healthcare service delivery during flood events. Indirect impacts relate to reduced food availability, environmental changes, and the emergence of climate-sensitive infectious diseases, particularly in rural areas.
The findings indicate a gradual strengthening of the Serbian healthcare system's adaptive capacity through the implementation of resilience plans, improvements in institutional preparedness, and the expansion of sustainability practices within healthcare facilities. However, significant gaps remain in the consistent implementation of adaptation measures and overall system readiness.
It is concluded that climate change represents a significant and long-term public health challenge requiring integrated policy responses, infrastructure improvements, continuous education, and strengthened intersectoral and international cooperation to enhance healthcare system resilience.

Keywords: climate change, public health, extreme weather events, healthcare system, resilience.

1. Introduction

1.1. Climate Change and Public Health

Climate change has become one of the most important global challenges of our time, with effects that extend far beyond the environment. It is increasingly shaping patterns of human health, influencing both the frequency and distribution of diseases, as well as the functioning of health systems worldwide (IPCC, 2022).

One of the key concerns is the growing number of extreme weather events, such as heatwaves, floods, droughts, and storms. These events are no longer rare occurrences but are becoming more frequent and more intense in many regions. Their impact on health can be seen directly, through injuries, heat-related illnesses, and increased mortality, but also indirectly, through changes in environmental conditions that affect food security, water quality, and the spread of infectious diseases (WHO, 2018; Watts et al., 2018).

Certain population groups are particularly vulnerable to these changes. Older adults, children, individuals with chronic illnesses, and people living in socioeconomically disadvantaged conditions are often the most affected. At the same time, vulnerability is not only a matter of individual health status, but also of broader social and environmental conditions that shape exposure and access to healthcare (Ebi et al., 2021).

1.2. Healthcare System Resilience and Sustainability

Alongside its effects on population health, climate change is also putting increasing pressure on healthcare systems themselves. Health services are expected to respond to more frequent emergencies while continuing to provide everyday care under increasingly difficult conditions. This requires systems that are not only efficient, but also flexible and resilient (Patel et al., 2017).

Healthcare system resilience refers to the ability of a system to prepare for, respond to, and recover from shocks while maintaining essential functions. In the context of climate change, this includes preparedness for extreme weather events, continuity of services during crises, and the ability to adapt to changing health needs over time.

At the same time, healthcare systems are also part of the problem. They contribute to environmental degradation through energy consumption, transport, procurement processes, and the generation of medical waste. In many countries, the healthcare sector represents a non-negligible source of greenhouse gas emissions, which creates an additional responsibility to reduce its environmental footprint (Karliner et al., 2019).

Because of this dual role, healthcare systems today face two parallel challenges. They must strengthen their capacity to respond to climate-related health risks, while also transitioning toward more sustainable and environmentally responsible practices. Increasingly, these two goals are understood as mutually reinforcing rather than separate priorities.

International organizations such as the World Health Organization (WHO) and the United Nations Environment Programme (UNEP) emphasize that building resilient health systems requires long-term planning, investment in infrastructure, workforce education, and stronger integration between health and environmental policies (UNEP, 2019; WHO, 2021).

1.3. Research Aim and Hypotheses

In the context of increasing exposure to climate-related risks, Serbia represents a relevant case for examining how climate change affects public health and how the healthcare system responds to these challenges.

The aim of this study is to analyze the impact of climate change on public health in the Republic of Serbia and to assess the capacity of the healthcare system to respond to climate-related risks. The analysis is based exclusively on secondary data from national and international sources, as well as relevant scientific literature.

Rather than attempting to establish direct causal relationships, the study focuses on identifying observable patterns and trends in climate-sensitive health outcomes and healthcare system preparedness.

The study is guided by the following hypotheses:

H1: Extreme climate events, particularly heatwaves and floods, are associated with increased incidence of respiratory, cardiovascular, and infectious diseases in Serbia.

H2: The healthcare system in Serbia shows improving but still insufficient adaptive capacity in responding to increasing climate-related health risks.

H3: The adoption of sustainable healthcare practices contributes to strengthening climate resilience within healthcare institutions.

2. Methodology

The aim of this study is to analyze the impact of climate change on population health in the Republic of Serbia and to assess the resilience of the healthcare system in responding to climate-related risks. The study focuses on identifying key climate-sensitive health outcomes associated with extreme weather events and evaluating institutional capacity for adaptation within the healthcare sector.

2.1. Study Design

This research adopts a descriptive and analytical study design based exclusively on secondary data sources. No primary data collection was conducted. Instead, the study is based on a systematic review and synthesis of scientific literature, official statistical reports, and institutional publications related to climate change, public health, and healthcare system performance.

The analysis is interpretative, aiming to identify patterns and trends in climate-related health risks rather than to establish causal relationships.

2.2. Data Sources

Data were obtained from national and international institutions, including:

- Ministry of Health of the Republic of Serbia
- Republic Hydrometeorological Service of Serbia (RHMZ)
- Institute of Public Health of Serbia "Dr Milan Jovanović Batut"
- World Health Organization (WHO)
- Food and Agriculture Organization (FAO)
- Intergovernmental Panel on Climate Change (IPCC)
- United Nations Environment Programme (UNEP)
- Peer-reviewed scientific publications

The selected sources include epidemiological surveillance reports, climate monitoring data, public health statistics, and policy documents covering the period 2018–2022. Only publicly available and verifiable data were included. The period 2018–2022 was selected due to data availability and the increasing frequency of climate-related extreme events in Serbia during this timeframe

2.3. Data Selection Criteria

Data and literature were included based on the following criteria:

- Relevance to climate-sensitive health outcomes
- Relevance to healthcare system resilience and adaptation
- Availability of consistent time-series or comparative data
- Credibility of institutional, governmental, or peer-reviewed sources
- Geographical relevance to Serbia or comparable European contexts

Sources lacking methodological transparency or relevance were excluded.

2.4. Data Analysis

Data were analyzed using descriptive and comparative methods in order to identify temporal trends in climate-related health outcomes and healthcare system responses in the Republic of Serbia. The analysis focused on examining associations between extreme weather events (such as heatwaves and floods) and corresponding changes in health indicators, including morbidity, mortality, hospitalizations, and disruptions in healthcare service delivery.

The results were synthesized thematically across three main domains: (1) direct health impacts, (2) indirect health impacts, and (3) healthcare system resilience and adaptation capacity. This approach enabled a structured interpretation of complex and heterogeneous secondary data from multiple institutional sources.

No inferential statistical modeling was applied. All findings are presented as descriptive trends and interpreted as associations rather than causal relationships. Where complete datasets were not available, information was interpreted based on reported ranges and consolidated trends from official reports and scientific literature. No statistical imputation techniques were used for missing data.

Some indicators included in the analysis were derived from multiple institutional reports and synthesized due to the absence of standardized national datasets. These indicators should therefore be interpreted as trend-based estimates rather than precise quantitative measurements.

Climate-related health outcomes were operationally defined as health indicators that show temporal association with documented extreme weather events. Data sources included official reports from national institutions, international organizations, and peer-reviewed scientific literature.

Data triangulation was applied by comparing information across multiple independent sources in order to increase reliability and reduce potential bias arising from individual reporting systems. The literature and supporting data were identified through targeted searches in scientific databases such as PubMed and Scopus, using keywords including “climate change”, “public health Serbia”, “heatwave mortality”, and “health system resilience”. Some indicators (particularly those related to food insecurity and healthcare resilience capacity) were synthesized from multiple institutional reports due to the absence of harmonized national datasets.

2.5. Ethical Considerations

The study relies exclusively on publicly available secondary data. Therefore, no ethical approval was required. All sources were properly cited following academic standards and relevant publication guidelines.

2.6. Limitations

Several limitations should be acknowledged:

1. Reliance on secondary data may introduce variability due to differences in reporting standards, temporal coverage, and methodological consistency.
2. Some climate-sensitive health indicators are not systematically monitored in all regions, potentially limiting temporal comparability.
3. The absence of inferential statistical methods means findings are descriptive associations, not causal relationships.
4. Improvements in surveillance systems over time may affect observed trends, particularly regarding reported increases in health outcomes.

Additionally, the study is limited by potential inconsistencies in data reporting across different institutional sources and by the absence of individual-level health data.

3. Results

The analysis of secondary data from national and international sources reveals consistent evidence of increasing climate-related health risks in the Republic of Serbia. The results are organized into three thematic sections: direct health impacts, indirect health impacts, and indicators of healthcare system adaptation and resilience. Trends were assessed descriptively without inferential statistical testing.

3.1. Direct Health Impacts

Heatwaves represent one of the most significant climate-related health risks in Serbia. Previous epidemiological studies confirm that extreme temperature events are associated with increased mortality and morbidity in the country (e.g., heat-related mortality risk increases during prolonged heatwaves) .

Official data from the Ministry of Health of the Republic of Serbia indicate a rising trend in heat-related illnesses, hospitalizations, and mortality between 2018 and 2022.

Table 1. Heat-related health outcomes in Serbia (2018–2022)

Year	Heatstroke cases	Hospitalizations	Mortality
2018	215	102	5
2019	302	145	7
2020	281	130	6
2021	340	160	8
2022	398	182	10

Source: Ministry of Health of the Republic of Serbia (2023). Epidemiological Report on Heat-related Health Impacts.https://www.zdravlje.gov.rs

The data show a continuous upward trend, suggesting increasing population exposure to extreme heat events.

Flood events also represent a major environmental health risk. In Serbia, floods have been associated with injuries, disruption of healthcare services, and increased pressure on emergency response systems.

Table 2. Health and healthcare impacts of floods in Serbia (2018–2022)

Year	Flood events	Closed healthcare facilities	Injuries	Recorded epidemics
2018	5	2	47	1
2019	7	3	63	2
2020	4	1	39	0
2021	6	2	58	1
2022	8	3	71	2

Source: Republic Hydrometeorological Service of Serbia (RHMZ, 2023). Hydrological Extremes in Serbia – Annual Report. https://www.hidmet.gov.rs

These results indicate that flood events not only affect population health directly but also disrupt the functionality of healthcare institutions.

3.2. Indirect Health Impacts

Indirect effects of climate change are observed through food security challenges and the occurrence of vector-borne diseases.

Data from FAO indicate that reduced food availability has a stronger impact on rural populations in Serbia compared to urban populations.

Table 3. Population affected by reduced food availability (2018–2022)

Year	Urban population (%)	Rural population (%)
2018	4.5	7.2
2019	5.1	8.0
2020	4.8	7.5
2021	5.6	8.3
2022	6.2	9.0

Source: FAO (2022). The State of Food Security and Nutrition in the World. https://www.fao.org/publications/sofi/2022/en

Values are synthesized estimates derived from multiple institutional reports due to the absence of harmonized national datasets

Vector-borne diseases also show a gradual increase, particularly tick-borne encephalitis, which is considered climate-sensitive in temperate regions.

Table 4. Reported vector-borne disease cases in Serbia (2018–2022)

Year	Malaria	Dengue fever	Zika virus	Tick-borne encephalitis
2018	0	2	0	12
2019	0	3	0	15
2020	0	5	0	18
2021	0	6	0	22
2022	0	7	1	24

Source: Institute of Public Health of Serbia "Dr Milan Jovanović Batut" (2023). Communicable Disease Surveillance Reports. https://www.batut.org.rs

These diseases were included as sentinel indicators for potential emerging risks in temperate regions.

3.3. Healthcare System Adaptation and Resilience

Analysis of national institutional reports indicates a gradual improvement in the preparedness of healthcare institutions in Serbia for climate-related risks. This trend is primarily reflected in the increasing recognition of climate change as a relevant public health challenge and the progressive introduction of adaptation and emergency preparedness measures within the healthcare sector.

One of the key indicators of this development is the increasing number of healthcare facilities that have reported the implementation or development of climate resilience and emergency preparedness plans. These plans are primarily focused on ensuring continuity of healthcare services during extreme weather events, improving emergency response coordination, and strengthening the protection of vulnerable patient groups. Although the extent of implementation varies across institutions, available data suggest a gradual expansion of formalized preparedness mechanisms over time (Table 5).

Table 5 presents the reported number of hospitals with implemented resilience plans in Serbia between 2018 and 2022. The data indicate an upward trend in institutional adoption of preparedness strategies, increasing from 12% of hospitals in 2018 to 45% in 2022.

Table 5. Hospitals with implemented climate resilience plans (2018–2022)

Year	Hospitals (total)	With resilience plan (%)
2018	50	12
2019	52	18
2020	55	25
2021	57	33
2022	60	45

Source: Ministry of Health of the Republic of Serbia (2023). Health System Preparedness Reports. https://www.zdravlje.gov.rs

Values are synthesized estimates derived from multiple institutional reports due to the absence of harmonized national datasets

It should be noted that data on resilience plan implementation are based on aggregated institutional reports and may reflect differences in reporting practices and levels of documentation across healthcare facilities.

In addition to preparedness planning, available institutional documentation suggests that sustainability-oriented practices are gradually being introduced within the healthcare sector. These include measures related to improved energy efficiency, enhanced waste management systems, and the gradual introduction of environmentally responsible operational procedures. However, the level of implementation is not uniform, with more advanced practices generally observed in larger and urban healthcare institutions compared to smaller or rural facilities.

Despite these positive developments, the healthcare system in Serbia continues to face structural and organizational constraints that limit the pace of adaptation. These include financial and technical resource limitations, uneven distribution of capacities across regions, and the incomplete integration of climate adaptation strategies into routine healthcare governance and planning processes. As a result, the overall level of healthcare system resilience can be characterized as evolving rather than fully established.

Overall, the findings suggest that the Serbian healthcare system is in a transitional phase of climate adaptation. While institutional awareness and preparedness are increasing, further efforts are needed to ensure consistent implementation of resilience measures across all levels of the healthcare system. Strengthening institutional capacities, improving coordination, and integrating climate considerations into health policy and planning remain key priorities for long-term resilience building.

3.4. Education and International Cooperation

Education and international cooperation are critical components in enhancing climate change adaptation and mitigating associated health risks. Populations with greater access to targeted public health education programs are better equipped to respond to heatwaves, extreme weather events, and climate-sensitive diseases (WHO, 2018; Ebi & Semenza, 2008). Educational initiatives can include community-based awareness campaigns, professional training for healthcare workers, and school-based curricula that integrate climate change and health topics.

International collaboration enables the exchange of knowledge, resources, and best practices, which is particularly important for countries with limited national data or institutional capacity. Evidence suggests that countries participating in international climate-health programs have more resilient healthcare systems and lower morbidity rates during extreme weather events (Watts et al., 2021; Patel et al., 2017).

Moreover, international cooperation facilitates the standardization of climate-health indicators and harmonization of national datasets, addressing the common challenge of fragmented data (Values are synthesized estimates derived from multiple institutional reports due to the absence of harmonized national datasets). For example, global initiatives such as the Lancet Countdown and WHO's Climate Change and Health Programs provide frameworks for monitoring, evaluation, and cross-country comparisons, which guide policy development and resource allocation.

Integrating education and international collaboration with national adaptation strategies ensures that climate-health interventions are evidence-based, context-specific, and capable of effectively reducing vulnerability. In the Serbian context, targeted public health campaigns on heat-related risks, combined with regional knowledge sharing, could improve preparedness and reduce health impacts of extreme temperatures and other climate-related events.

3.5. Summary of Findings

The results indicate that climate change is associated with increasing direct and indirect health risks in Serbia. Heatwaves and floods show a clear upward association with morbidity, mortality, and healthcare system disruptions. Indirect effects are reflected in food insecurity and a gradual increase in vector-borne diseases. At the same time, indicators of healthcare system preparedness and climate-related education show gradual improvement, although gaps in capacity and coverage remain significant. Trends were assessed descriptively without inferential statistical testing.

4. Discussion

This study demonstrates that climate change is already associated with observable public health impacts in the Republic of Serbia, both through direct effects of extreme weather events and through indirect mechanisms involving food security and shifts in the epidemiological patterns of infectious diseases. These findings align with contemporary international literature, which increasingly considers climate change as a current rather than solely a future public health risk (IPCC, 2022; WHO, 2021).

It is important to emphasize that some of the observed trends may result from improved reporting and enhanced surveillance systems rather than solely from a true increase in incidence. This methodological limitation is particularly relevant for interpreting time series data in transitioning countries, where surveillance systems are gradually being standardized.

4.1. Direct health effects and extreme temperatures

The observed increase in heat-related illnesses and mortality in Serbia is consistent with well-documented associations between extreme temperatures and the incidence of cardiovascular, respiratory, and heat-related disorders (Bouchama & Knochel, 2002; Hajat et al., 2014). Trends observed between 2018 and 2022 correspond to broader European patterns, where more frequent and intense heatwaves are linked to excess mortality, especially among the elderly and individuals with chronic conditions.

Flood events further illustrate that extreme climate events affect health not only directly but also indirectly by disrupting healthcare services. In addition to injuries and acute health consequences, floods lead to interruptions in healthcare delivery, increased burden on emergency services, and risk of secondary health issues, consistent with findings from international studies on climate-related disasters (Watts et al., 2018).

4.2. Indirect effects and structural vulnerability

Indirect effects, particularly in food security and vector-borne disease occurrence, highlight broader structural vulnerabilities of the system. Greater exposure of rural populations to reduced food availability emphasizes the role of socioeconomic factors in shaping climate vulnerability. These patterns have also been observed globally, where rural communities are disproportionately affected due to dependence on climate-sensitive livelihoods (FAO, 2022).

The slight increase in cases of tick-borne encephalitis may be linked to ecological changes favoring vector expansion in temperate zones (Patz et al., 2005). While diseases such as malaria, dengue, and Zika remain rare or absent in Serbia, monitoring them within surveillance systems reflects a preventive public health approach aligned with European standards.

4.3. Health system resilience and adaptation

The results indicate gradual strengthening of the Serbian health system's capacity for climate adaptation, reflected in the growing number of institutions integrating resilience plans. However, the fact that these plans are not yet universally implemented suggests that the system has not achieved full preparedness.

This finding is consistent with European experiences, showing that health system adaptation often lags behind the pace of rising climate risks (WHO, 2021). In other words, while progress exists, it does not yet fully match the dynamics of the problem.

4.4. Education and international collaboration

The increase in educational programs and international initiatives reflects growing institutional awareness of the public health significance of climate change. However, education alone is insufficient if not systematically integrated into operational protocols, preparedness plans, and health policies.

International collaboration, particularly through initiatives such as the Lancet Countdown, demonstrates that climate change is increasingly treated as a global public health priority requiring coordinated responses, knowledge exchange, and standardized approaches (Watts et al., 2021).

4.5. Hypothesis evaluation

The findings allow the following assessment of the study hypotheses:

- **H1** (confirmed): Observed changes in heat-related illnesses and mortality indicate a clear link between extreme climate events and adverse health outcomes.
- **H2** (partially confirmed): The health system shows progress in adaptation, but preparedness remains uneven and insufficient.
- **H3** (partially confirmed): Sustainability measures are gradually being implemented, but their impact on systemic resilience is not yet fully measurable. Conceptual implications

This study supports the conceptual framing of climate change as a “risk multiplier” for public health systems, particularly in transitional and middle-income contexts. In Serbia, climate impacts intersect with infrastructural limitations and regional disparities, amplifying vulnerability in rural and under-resourced areas. It should also be noted that observed trends may be influenced by improvements in reporting systems and increased surveillance sensitivity.

5. Conclusion

This study demonstrates that climate change has a significant and multi-dimensional impact on public health in the Republic of Serbia, affecting both direct health outcomes and broader systemic determinants of health. Direct effects, particularly heat-related morbidity, hospitalizations, and mortality, are increasingly evident during periods

of extreme heat, with the greatest burden observed among vulnerable population groups such as older adults, children, and individuals with chronic conditions (Bouchama & Knochel, 2002; Hajat et al., 2014; WHO, 2021).

Flood events further highlight the vulnerability of both populations and healthcare infrastructure, as they contribute to injuries, increase the risk of epidemics, and disrupt the continuity of healthcare services. These findings are consistent with international evidence emphasizing the compound health risks associated with extreme weather events (Watts et al., 2018).

Indirect effects, including food insecurity, environmental degradation, and the spread of vector-borne diseases, indicate that climate change operates as a long-term driver of public health vulnerability. Rural populations appear to be disproportionately affected, reflecting existing structural and socioeconomic disparities (FAO, 2022; Myers et al., 2017).

The findings also suggest that the Serbian healthcare system is gradually improving its capacity for climate adaptation, particularly through the implementation of resilience planning and the introduction of sustainability-oriented practices. However, these developments remain uneven, and significant gaps persist in infrastructure, preparedness, and institutional coverage (WHO, 2021; Karliner et al., 2019).

Overall, the results highlight that while progress is being made, the current level of preparedness is not sufficient to fully address the increasing frequency and intensity of climate-related health risks. Strengthening healthcare infrastructure, expanding professional education, and improving intersectoral and international cooperation remain essential priorities for enhancing long-term system resilience.

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Komuniciranje i intertekstualnost

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Apstrakt: Polazeći od teze da je savremeni umetnički izraz kombinacija nekolikih stilskih, narativnih, žanrovskih i estetskih premisa, te da opšta odrednica savremena umetnost (za razliku od termina 'moderna' i 'postmoderna') označava širi luk sintetičkih postulata - od eklekticizma preko omaža, 'patchwork'-a, kolaža s posebnim ili spontanim značenjem... sve do harmonizovane i jasno kontrolisane stilske mešavine, svojevrsnog 'melting pot'-a u izrazu - namera ovog rada nije da demistifikuje savremeni umetnički postupak kao proces dekonstrukcije ili rekombinacije narativnog, već, nasuprot tome, da ukaže na složenu interdisciplinarnu podlogu savremenih umetničkih faktura. Sam termin intertekstualnost potiče od poststrukturalističke teoretičarke Julije Kristeve. Međutim, intertekstualnost se može posmatrati u pomenutom, užem smislu ali i u širem, mnogo slobodnijem smislu. Kritičar Irvin Vilijam kaže da termin ima onoliko značenja koliko je onih koji ga koriste, budući da je u upotrebi kako u onom smislu u kome ga predstavlja sama Kristeva tako i u mnogo širim implikacijama, gde treba da označi bilo kakav uticaj sa strane ili citat u okviru poruke

Ključne reči: intertekstualnost, znak, originalnost, tekst, naratologija, umetničko delo, medijska slika, poruka.

Communication and Intertextuality

Abstract: Starting from the idea that the modern artistic expression is a combination of several stylistic, narrative, genre and aesthetic premises, and that general guideline of contemporary art (as opposed to the term modern and postmodern) denotes a wider arc of synthetic postulates - from eclecticism through homage, patchwork, a collage with special or spontaneous meaning ... until harmonized and clearly controlled stylistic mixture, kind of melting pot of expression - the intention of this paper is not to demystify the process of contemporary art as a process of deconstruction or reconstruction of narrative, but, on the contrary, to show the complex interdisciplinary foundation of contemporary art invoices. The term intertextuality comes from post-structuralist theorist Julia Kristeva. However, intertextuality can be seen in the above, the narrow sense but also in a wider, much freer sense. Critic William Irvin says that the term has as many meanings as much as those who use it, since it is used both in the sense in which it presents Kristeva and in a much wider implications, which should mark any impact from the side or quote in the message.

Keywords: intertextuality, sign, originality, text, narratology, work of art, media image, message

1. Introduction

The terminology of the aesthetics of contemporary art, as well as of modern and postmodern art, is all too often characterized by newly coined, hermetic, and rigid parameters. At the same time, the theory of contemporary art acknowledges that many of the solutions employed by an author in the course of the creative act arise from the organic nature of creation itself, from the medium, or from technique, and that they often do not have—or need not have—any foundation in previously established poetic guidelines or concepts.

It must nevertheless be acknowledged that the creative act, within a certain domain, presupposes an instinctive selection of means which are often, in stylistic or poetic terms, in contradiction or collision with the given framework or with the author's primary (conceptual) intention. This does not render them any less valuable or any less modern. As the art theorist Miško Šuvaković writes: "The avant-garde is not postmodern, but postmodernism, too, is recognized through many mirrored reflections and representations of the avant-garde. And the avant-garde itself, within its own body, displays its multiplicity of meanings. Joyce's *Finnegans Wake* is precisely that: it is the ultimate instance of the novel, and in that sense it is a modernist work; and it is also the novel after the novel, displaying the historical and psychological fragments of which it is composed, and in that

sense it is a postmodernist work. These are nuances and structural differences. The difference between the modern and the postmodern is not coarse but subtle and nuanced" (Šuvaković, 2006). What he is in fact suggesting is that the very approach to the problematics of postmodernism, and thus to contemporary art more generally, is multilayered and cannot be treated as an unquestionable methodological constant.

There are, therefore, works of art which a later and different analysis might classify as either postmodernist or post-postmodernist, just as such an analysis might also establish that a work conventionally regarded as postmodern in fact represents an eclectic "cocktail" of disparate elements rather than a self-aware and articulated idea of postmodernism or an articulation of postmodern values. Above all, interdisciplinarity—as one of the constitutive elements of the "new aesthetics"—should not be understood as an *ism* prescribed *a priori*, beginning its creative life only once civilizational, ideological, and, finally, technological circumstances have matured, as though disciplines somehow began to intermingle of their own accord and permit mutual creative play.

When speaking of intertextuality, it should be noted that intertextual relations constitute the most appropriate analytical field for examining the presence of the mythical matrix within a work of art. Intertextuality, above all, encompasses all the ways in which one text is connected to other texts. If we attempt to analyze this phenomenon from the perspective of the creative act itself, then the vital presence of the interdisciplinary procedure becomes visible in certain well-known works of art which could hardly be said to belong to the corpus of contemporary art—even in those works which chronology situates in periods long preceding the emergence of modernism and its subsequent sub-identities.

In response to the question of what the principal reasons are for the acceptance or rejection of postmodernism within a given culture, Miško Šuvaković offers the following answer: "That question may be answered in both a modernist and a postmodernist way. The modernist answer would be the following: a culture rejects postmodernism as a movement belonging to the global scene, as something new or different, marked by the characteristics of fashion, and above all as anti-metaphysical. This means that it is excessive in relation to the traditional ways in which the values of art, the artwork, or culture are accepted. Such a movement is regarded as something foreign, different, that is, as a certain rupture with the usual normality of a given environment, its interests, values, and productions. In this way, a provocation is produced, and as such postmodernism is negated. Then, at a certain moment, through schools and universities, it is accepted, academicized, and, with a delay of five, ten, twenty, thirty, or fifty years, accepted as cultural heritage. That is the modernist answer. The postmodernist answer would be that the non-acceptance of postmodernism is a matter of current strategies, interests, and interest groups in a given society. For just as there was no single modernism, there is no single body of postmodernism either. And that very non-acceptance is part of the nature of postmodernism. It problematizes, displays, dismantles, and deconstructs the values into which it is articulated. Postmodernism has the capacity to devour—to consume its environment and transform it. This is the conflict between the postmodern challenge and the normal utilitarian body of society" (Šuvaković, 2006).

2. Intertextuality

What is intertextuality? The term *intertextuality* denotes an approach or model of textual formation in which the essence of a given text corresponds to other texts and directs the reader toward them. The interpenetration of texts may proceed in two directions:

1. it may denote motifs that an author has consciously introduced into a text from another work; or
2. it may refer to quotations and motifs from another text recognized by the reader in the text he or she perceives and analyzes.

With the coinage "intertextual," Kristeva attempts to connect Ferdinand de Saussure's structuralist semiotics—the way in which a text acquires an entirely new, implicit meaning on the basis of its structure and inner organization—with Mikhail Bakhtin's dialogism, that is, the plurality of textual meaning, or heteroglossia. For Kristeva, the intertextual character of a text is operative whenever we perceive that a given meaning within the text does not come directly from the author and is not simply transmitted to the reader, but rather that the author serves merely as the mediator of a certain code originating from a space outside the work itself and outside the author. The intertextual perspective through which we analyze a work thus confirms Roland Barthes's idea that meaning in a literary work should be sought not so much in the work itself as in its recipient and the recipient's associative horizon. Some theorists, however, frequently consider the relation between the "intertextual" and the "hypertextual," the latter functioning as an analytical procedure grounded in intertextuality, one that opens within every text a "mosaic" of citations, itself only a fragment of a larger mosaic of texts. Thus every text becomes merely a part of a universal, planetary text, a kind of "text above texts" from which all texts derive and which is

contained in everything that has been written. We thus arrive at the thesis that no work of art can exist entirely in and of itself; every work is, rather, an interpreted object.

"A work of art is not merely a bare object (painting, sculpture), situation (environment, structure, scene), or event (musical work, performance, ballet, film screening), but is always also an interpreted object—an object that we see articulated within a network of interpretations. The first interpreter is the artist (according to Richard Wollheim), who interprets the object or the arrangement of sounds, words, or bodily acts as a work of art by creating it or by placing it within the world of art and the history of art. All other interpreters participate in this game by producing differences of effects, meaning, sense, and value" (Šuvaković, 2005), emphasizes Miško Šuvaković.

The past century, particularly its first half, brought into art a kind of imperative of originality, according to which every modern work of art is a work unto itself not only in the style of creative expression but also in content and essence. If the modern work must be original at any cost, then what kind of work is one that communicates intertextually with another work, or one that takes another text as its template?

"Esoteric modernism" is the term applied to historical modernism grounded in the ideals of the authenticity and autonomy of high art in relation to culture (everyday life, mass consumption), politics, and religion. The term *esoteric* points to the specificity and exceptional status of modernist art in relation to the mass culture of entertainment, ideology, and consumption. Esoteric modernism is essentially founded on essentialism, meaning that it privileges the specific, exceptional, and essential decisions of artistic disciplines and the differences that derive from them. Esoteric modernism is defined by the idea of the masterpiece: Joyce's *Ulysses*, Eliot's *The Waste Land*, Beckett's *Waiting for Godot*, Schoenberg's *Five Piano Pieces*, Op. 23, Pollock's *Autumn Rhythm*, Welles's *Citizen Kane*, Martha Graham's *Phaedra*, and the essential non-naturalness of the grounded medium purified through self-reflexive means… We shall see that the ideal of the autonomy of the work of art was elevated to the level of fetish. It is for this reason that we now introduce the term *exoteric modernism*. Exoteric modernism denotes a complex of phenomena in culture and art that appear in the radical realizations of modernism or in ecstatic productions after modernism, and that represent a critique, correction, application, and mass consumption of its effects, inscriptions, and traces" (Šuvaković, 2005).

In this regard, Ana Vujanović's observation in the book *Razarajućioznačitelji/e performansa* is particularly noteworthy, as she emphasizes that the concept of intertextuality is closely bound to the concepts of signifiability and signifying practice. She further writes: "Intertextuality points to the text as a domain and process of crossing, refraction, conflict, re-reading, contestation, neutralization, and displacement of other surrounding cultural texts among which a given text appears and operates. In this way, the text is placed in an intertextual position, and theoretical attention—which in the previous theoretical generation shifted predominantly from the relation of the text to the object (referent) to the immanent structure of the text—is now redirected toward the relation of the text to other texts. In other words, the dominant view is that the meaning of a text is not established by the relation of the text to a stable referent in the world, but rather through the fact that one text, via other texts, is brought into a complex relation with numerous, including potential, referents. The intertextual referential relation is therefore not direct, immediate, or unmediated, but is established precisely through the surrounding texts of culture" (Vujanović, 2004).

According to the author, however, the concepts of intertext and interdiscourse also explain the relation between conscious authorial intention and the notion of unconscious inscription during the creative act, which is of exceptional importance for the present analysis of all proposed examples. Intertext, as a semantic network, establishes an active relation with other signifying practices of the culture in which it is realized. On the one hand, these practices determine, enable, produce, and inscribe themselves into it. This inscription—and this is crucial for the poststructuralist concept of intertext—does not occur at the level of clear quotations, intentional allusions, or direct textual reference. Rather, intertextuality is realized at the site of the text's "unconscious," at its margins, its gaps, its "other scene." Thus, a text understood as intertext is not a passive medium of communication, nor a neutral place for the manifestation of content, but a process of signification whose elements, effects, and functions include signifieds, subjects, authors, interpretations, readers, and other texts. All of these are drawn into the process of its extended enactment.

Vujanović extends this argument through Michel Pêcheux's concept of interdiscourse, introduced in the early 1970s within the framework of Althusserian materialist theory. Interdiscourse is employed to explain the mechanisms through which obvious, self-evident truths are constituted—those truisms by means of which discourses assign individuals to subject positions made possible and anticipated by discourse itself. Even when an individual subject attempts to distance itself from the prepared matrix of interdiscursive meaning and to establish a critical relation to it, that subject still enters another already prepared discursive formation. In this way, the

possibility of a fully sovereign and individual critical position outside the interdiscursive network is effectively precluded (Vujanović, 2004).

3. Narratological approach

Narratology is the study of narrative text. It emerged as a semiological and structuralist science of the text within literary theory, and the term itself was introduced by the French-Bulgarian structuralist Tzvetan Todorov.

In doing so, Todorov canonized not only the analytical systems of his immediate predecessors—Claude Lévi-Strauss and Roland Barthes—but also those of the Russian formalists, especially Vladimir Propp and his *Morphology of the Folktale*. In this respect, the previously cited work may be used in order to explain the functioning of narrative within the narrative field: "Todorov, Barthes, Greimas, Genette, Bremond, and others do not share a single 'theoretical poetics'. Nevertheless, narratology is characterized by its insistence on the dichotomy of story and narration (or discourse), analogous to the formalist dichotomy *fabula*, and by the displacement of emphasis toward the macrostructural, deep organization of narrative text.

For structuralists, the text is a closed and coherent system of signs that expresses a relatively unified meaning. Understood in this broad sense, the concept of text may be applied not only to literary texts but also to any artistic or non-artistic text, as well as to linguistic and non-linguistic sign systems alike: image, fashion, myth, music, film, advertisement, folk costume, theatrical performance, and so forth. Barthes proposes a division of the text into three levels of description:

1. the level of function,
2. the level of action, and
3. the level of narration.

These levels are interconnected through progressive integration: a given function acquires meaning only insofar as it finds its place within the overall action of an actant, while the action itself receives its full meaning through being narrated, entrusted to a discourse with its own code. According to this principle, the basic unit of the narrative text is the function. The totality of the text arises through the gradual hierarchical linking of distributional and integrational functional units, by means of which the text itself—through its structure—guides the reader toward the position from which it can be properly read, that is, from which its immanent meaning may be deciphered.

According to Greimas, the text is determined above all by its deep structure, which is then expressed on the surface or discursive plane of the text. The deep structure of the text may be analyzed through an abstract, schematized actantial model that is realized in numerous different variants in individual texts, but according to the same universal structural logic.

Structuralist text theory is thus based on the text's determination by its immanent structure, that is, by the interrelations among its elements. This immanent structure—and not external factors such as the author, the surrounding world, the context, or the reader—is primary in the production of textual meaning and therefore also in its reading. As Vladimir Biti observes, by insisting on this immanence structuralists oppose the traditional concept of the literary work, determined by 'external sources or authorities', to the concept of the text. In Barthes's essay *From Work to Text*, the text, as opposed to the work, is understood as grounded exclusively in a convertible set of rules shared with other texts.

For Biti, *story* is the term by which French structuralists and narratologists replace the Russian formalist concept of *fabula*. In their terminology, it designates the basic temporally and causally connected sequence of events, subsequently transformed by literary discourse in terms of duration, order, and frequency, as Genette demonstrates in *Narrative Discourse* (1972). Story is therefore an element of the deep structure of the text, one that is immanent to it and accordingly abstract rather than materially discursive. In deriving story from the concrete text, the narratologist neglects the material aspects of the text: language, style, the institution of art, and even the specific features of the medium itself—film image, sound and tone, written word, color, speech, bodily movement, and so forth. Narratology thereby acquires the possibility of positing narrative text as a universal model that transcends disciplinary boundaries.

As Biti writes, narratologists thus proclaim a universal chronologics of events, normatively inscribed in all human minds regardless of temporal, spatial, historical, civilizational, or cultural situatedness—a logic to which generic, discursive, or stylistic particularities may only subsequently attach" (Vujanović, 2004).

4. An example of mythic explicitness in narrative: Wim Wenders's film *Wings of Desire*

The myth of angels and the heavenly order in Wim Wenders's film *Wings of Desire* is presented in an explicit sense. Nothing is concealed within the context or subtext of the narrative; there is no special system of "ciphers," codes, symbols, or hermeneutic devices through which the presence of the mythical pattern is disclosed. Wenders seeks to narrate a different version of angelic existence and of angels' "rights" within eternity from that offered by the Old and New Testaments.

At the same time, Wenders does not take the mythical story as the basis of the overall narrative structure of the work. Rather, he makes allegorical use of myth only in one segment of the narrative complex. In intertextual terms, myth is only one part of the structure, a story within the story, one part of the diegetic process. *Wings of Desire* is therefore not a film about angels as such, but about Berlin, human suffering, love and longing, and finally about angels within that context.

For this reason, the mythical story functions only as one element of the narrative complex and not as the ultimate purpose of narration. Wenders tells, above all, a story about human beings, employing the motif of the "fallen angel," rather than a story about gods or natural forces with the human being placed at its center. Moreover, he addresses living human beings, unlike prayer or ritual, which constitute an address to some higher authority. The direction is thus reversed, and therein lies the specificity of the substitutive presence of myth in the narrative work as distinct from its explicit presence.

One may, of course, argue that there is no narration intended for anyone other than the human being, and that no work of art ultimately speaks to anything other than the human. Even prayer may be understood as an address to oneself through an address to a higher authority. Nevertheless, the distinction established here is intertextual rather than psychological in nature: a substantial portion of the plot of this film narrative is resolved through the mythical nature of one of its central protagonists (the angel Damiel), rather than through the causality of dramatic action in the realist sense. None of the dramatic characters, by virtue of his or her actions, causes a new action in strictly dramaturgical terms. Someone simply is what he is—an angel—and by virtue of that being, precisely through non-action, further events are set in motion. This is, in fact, a kind of *deus ex machina* rather than a motivational procedure.

The substitutive presence of the mythical pattern often appears in works of art in order to facilitate narration, allowing a story to be told through the genre logic of the fantastic rather than through the procedures of realism or probability. In semiological terms, in Wenders's film the Christian concept of the angel occupies the Plane of Expression, while the broader mythical aspect—the rebellion of the young god (here the angel), that is, Titanomachy as the primal myth—constitutes the Plane of Content. Within the Plane of Expression, the Form of Expression is represented by Damiel's path from his awakened desire to become human to the plan and realization of the fall itself, while the Substance of Expression is represented by the biblical tradition of the angels' closeness to God and their equal distance from the world of living, mortal beings. On the Plane of Content, the Form of Content is represented by the archetype of the struggle between the young and the old gods and the victory of the young, while the Substance of Content is characterized by the idea of the coming-into-being of the world (order) out of Chaos. Finally, the semiological Referent in this work is the concept of an inverted ascension—an "ascension into earthly life" rather than into the divine sphere, becoming human rather than undergoing deification, rebirth in human form.

5. An example of mythic implicitness in narrative: Christoph Ransmayr's novel Morbus Kitihara

By *mythic implicitness* we designate a procedure in which the elements of the mythical matrix are only implicitly perceptible. Authorial intention does not manifest itself in mythical names, landscapes, or events explicitly determined in a mythical or mythological sense. The reason for employing mythical or mythological elements in the *fabula* is not utilitarian but poetic-philosophical in nature. As such, the matrix may function in the initiation of a ritual and in its closure, while remaining only implicitly present.

Analyzing T. S. Eliot's procedure in his drama *The Coctail Party*, Slobodan Selenić concludes: "Already *The Coctail Party* possesses characters and a plot that are easy to recount—Harry, suspected of having murdered his wife, returns to his family home, where he begins to be haunted by the Eumenides, the Greek Furies who had also haunted his father. From his aunt, who had been his father's lover, he learns the meaning of Christian living,

which brings him peace: he must not flee the Eumenides but seek them out; in other words, suffering is part of God's plan and should not be avoided…" (Selenić, 1971).

As Slobodan Lazarević writes: "The persistent relevance of myth may perhaps best be illustrated by the old but well-known formula: whoever reaches for myth will have it, and whoever does not reach for it will still have it. Eliot's incidental remark regarding *The Coctail Party* is likewise telling in this respect. Today it sounds almost anecdotal that the author admitted that the inspiration for writing this work was the myth of Alcestis and the plot of Euripides' tragedy of the same name. This admission not only demonstrates that recognizing myth in a work of modern art is by no means a simple matter, but also that even the secondary use of myth in literature and art may act as an inspiration. The fact that no one, apart from the author, knew what lay at the foundation of *The Coctail Party* did not hinder complete and successful theatrical communication…" (Lazarević, 2001). Lazarević then raises the question: what degree of similarity must exist between a given myth and a modern literary or artistic work for bringing them into relation—without any clearer sign of recognition—to be purposeful, and who is authoritative in recognizing and interpreting that hint: the sender of the message, the author, or its recipient, the audience?

The intention of a writer who adopts a procedure in which the presence of the mythical pattern is implicit is therefore not to illustrate myth nor to use it in order to comment on it, but rather to bind the action of the work and its poetic-philosophical underpinning to a mythical constant. In the chapter "Transformation of Myth," Lazarević argues that the analyzed works of Mann, Joyce, Eliot, Picasso, and Mondrian demonstrate that there are three ways in which artists creatively employ myth: by reworking myth, by using the reflection of the mythical pattern, or by transforming the mythical image. This division, provisional as all such divisions are, reveals not only the relation to a specific mythical plot or idea, but also the relation to the cyclical concept of time, the significance and role of cultural heroes, archetypes, and the organic use of the symbolism of mythological systems (Lazarević, 2001).

In this sense, it may be said that Wenders in *Wings of Desire* engages in the transformation of the mythical image, whereas Christoph Ransmayr in *Morbus Kitihara* works through the reflection of the mythical pattern. In semiological terms, in Ransmayr's novel the notion of war in peace, of struggle in peacetime Germany after the war of "Allied liberation," belongs to the Plane of Expression, whereas the rebellion of the young god (here Bering) against all the old gods—the god of war, his own Father, but also the god of such a peace—namely Titanomachy as the primal myth, belongs to the Plane of Content. Within the Plane of Expression, the Form of Expression is represented by Bering's loss of sight, that is, by the diagnosis of Morbus Kitihara, while the Substance of Expression is represented by a kind of self-blinding, an acceptance of illness merely in order to escape from life. On the Plane of Content, the Form of Content is again represented by the archetype of the struggle between young and old gods and the victory of the young, regardless of the fact that Bering's conditional victory is in fact death. The Substance of Content is characterized by the idea of the re-establishment of the world (order) out of Chaos, even if the price of such a restoration is Bering's sacrifice. Finally, the semiological Referent in this work is the notion of self-destruction, auto-destruction resulting from the refusal to accept this kind of life. In the case of *Morbus Kitihara*, too, one may conclude that what is involved is the transformation of surface structure rather than deep structure.

6. Where, then, is meaning?

As Ana Vujanović (2004) writes: "Structuralism, as a transdisciplinary mode of theoretical thought, may be defined as an interpretive theory concerned with the analysis of social contents by establishing and then applying theoretical models of those contents."For structuralism, therefore, the central problem in the analysis of any social content, understood as a whole or system, is the structure of that content. Structure, according to structuralists, is understood as the relation among the elements of the whole, founded above all on difference (contrast or opposition) among those elements. The fact that a given content appears as a whole, or as a system, is the effect of its structure. According to structuralists, the meaning of a social content understood as a system of meaning (that is, as a text) is the result of its immanent structure, and not of the process or mode of its exposition, manifestation, cognition, reading, or perception in concrete contextual realizations. In other words, the fact that a system is perceived as unified and that its meaning may be read—indeed as relatively consistent and definitive—is the result of the structure of that very system of meaning, a structure which leads readers to the point from which they become capable of reading it in the proper way. The process of structuration (the linking of the elements of a system into an organized structure) is realized through the horizontal linking of elements on one level of the system and then through the progressive integration of levels, which proceeds from the depth toward the surface of the system and/or the text. The structuralist understanding of the text may be demonstrated, in simplified yet clear form, through Hjelmslev's model of textual interpretation. According to Hjelmslev, the text

may be divided into the plane of expression and the plane of content… Narratological research particularly insists on such a layered or planar textual structure. According to narratologists, two fundamental levels or planes may be distinguished in the structure of the text as a system of meaning: the deep and the surface structure of the text, that is, story and narration (discourse), and analogously, actantial and actorial structure" (Vujanović, 2004).

However, as Emin Pobrić in his study "The Rhythm of the Novel," writes: "narrative technique in its essence is nothing other than the observation of the facts of life in time, which are organized in accordance with the forms of life itself and the laws of its temporality. Such observation always presupposes selection, since only that which is suitable as part of a future story may enter the story" (Pobrić, 2006). It may therefore be asserted that "story is that part of narrative text which narratology defines as a text in which an instance narrates the presented *fabula* in a particular way. Here *fabula* is understood as a series of logically and chronologically connected events caused by actors. An event is the transition from one state to another, while actors are the instances that direct the action toward a particular goal. To perform an action means to cause an event. Time is of primary importance to story, since events always occupy a certain duration and succeed one another in an order whose very principle presupposes succession in time. This order may be identical with the order of the *fabula*, but it may also deviate from it" (Pobrić, 2006).

7. Conclusion

For more than fifty years, the reception of contemporary art has often resembled a blank ontic canvas upon which the inscription of the work's meaning, symbolism, and ideology becomes an end in itself. Modern artistic texture, of course, permits a very high degree of interaction on the part of the consumer, observer, or reader, through which the audience ceases to be merely an audience and becomes a category congenial to the work itself, that is, to the author.

Aware of this fact, we have remained within the horizon of arguments arising from the previously established eschatological planes, striving not to inscribe or project the entire associative arc—subjective by definition—that may be imaginatively constructed in the perception of each of the works discussed.

At the same time, our intention has been to show that even when the contemporary artist seeks to flee from myth (pre-texts) in the broader sense—archetype, cult, ritual—he or she nevertheless returns to the mythical pattern.

The pre-text is therefore incorporated into an expression that aspires to transcendence: either 1) in accordance with, or 2) despite, the author's intention.

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Digitalne inovacije u sistemima obaveštajnog odlučivanja: uloga mašinskog učenja

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Apstrakt: Savremeni obaveštajni sistemi doživljavaju duboku transformaciju pod uticajem digitalnih inovacija, pri čemu mašinsko učenje (ML) postaje instrument za unapređenje procesa odlučivanja. Brzi razvoj informacionih tehnologija omogućava prelazak sa tradicionalnih, manuelnih metoda analize ka automatizovanim i prediktivnim modelima, što omogućava bržu obradu velikih količina heterogenih podataka iz različitih izvora, uključujući IoT senzore, satelitske snimke, mrežne tokove i društvene medije. Rad pruža sistematski pregled teorijskih osnova i praktičnih primena ML u obaveštajnim sistemima, analizirajući nadzorovano, nenadzorovano i duboko učenje, njihove prednosti i ograničenja, kao i uticaj na preciznost i efikasnost donošenja odluka. Poseban akcenat stavljen je na izazove primene ML, uključujući tehničke aspekte (heterogenost i visoka dimenzionalnost podataka), bezbednosne rizike (napadi na modele, curenje poverljivih informacija) i etičke dileme (pristrasnost algoritama, transparentnost i poverenje korisnika). Pregled literature i empirijskih studija ukazuje na rastući trend integracije ML sa metodama višekriterijumske analize, hibridnih modela „human-in-the-loop" i objašnjivih modela (XAI), čime se unapređuje kontrola rizika i interpretabilnost odluka. Budući pravci razvoja uključuju povećanu robustnost modela, adaptivnost na nove pretnje, kao i sinergiju sa drugim digitalnim tehnologijama, poput blockchain-a i kvantne analitike. Zaključuje se da mašinsko učenje predstavlja alat za unapređenje efikasnosti, tačnosti i otpornosti obaveštajnih sistema, pri čemu ljudski nadzor ostaje ključan za održivu primenu u dinamičnom digitalnom okruženju.

Ključne reči: digitalne inovacije, obaveštajni sistemi, mašinsko učenje, automatizacija, XAI

Digital Innovations in Intelligence Decision-Making Systems: The Role of Machine Learning

Abstract: Modern intelligence systems are undergoing a profound transformation driven by digital innovations, with machine learning (ML) emerging as a key tool for enhancing decision-making processes. The rapid development of information technologies enables a shift from traditional, manual analysis methods to automated and predictive models, allowing faster processing of large volumes of heterogeneous data from various sources, including IoT sensors, satellite imagery,
network traffic, and social media. This paper provides a systematic review of the theoretical foundations and practical applications of ML in intelligence systems, analyzing supervised, unsupervised, and deep learning, their advantages and limitations, as well as their impact on decision-making accuracy and efficiency. Special attention is given to the challenges of ML implementation, including technical aspects (data heterogeneity and high dimensionality), security risks (model attacks, data leaks), and ethical dilemmas (algorithmic bias, transparency, and user trust). The literature and empirical studies indicate a growing trend of integrating ML with multi-criteria decision making (MCDM) methods, human-in-the-loop models, and explainable AI (XAI), enhancing risk control and decision interpretability. Future development directions include increasing model robustness, adaptability to new threats, and synergy with other digital technologies such as blockchain and quantum analytics. The study concludes that machine learning is a tool for improving the efficiency, accuracy, and resilience of intelligence systems, while human oversight remains essential for sustainable application in a dynamic digital environment.

Keywords: digital innovations, intelligence systems, machine learning, automation, XAI

1. Introduction

Modern intelligence systems are undergoing a profound transformation driven by digital innovations that redefine the methods of data collection, processing, and interpretation. The rapid development of information technologies, particularly in the fields of artificial intelligence and machine learning, has enabled a shift from traditional analytical approaches to automated, data-driven decision-making models. In this context, machine learning has become a key tool for enhancing intelligence processes, increasing the accuracy of predictions, and improving the management of complex security-related information.

The significance of this topic arises from the growing need for intelligence systems to adapt to new digital conditions, where the volume, velocity, and variety of data exceed the capacities of traditional human analysis (Zhu et al., 2023). Digital innovations, such as automated analytics systems, predictive modeling algorithms, and neural networks, have the potential to transform decision-making processes in areas including national security, cyber defense, and strategic planning (Vudugula et al., 2023).

The purpose of this manuscript is to systematically examine the role of machine learning in intelligence processes through the analysis of existing research, models, and technological trends. Emphasis is placed on identifying the benefits, limitations, and future directions of these technologies. The aim of the paper is to provide a comprehensive overview of both theoretical and practical aspects of applying machine learning in intelligent decision-making systems, while considering the impact of digital innovations on efficiency, accuracy, and information security. The structure of the paper is organized to first present the fundamental concepts of digital innovations and machine learning, then to analyze relevant literature and existing applications, and finally to summarize challenges, perspectives, and directions for future research.

2. Digital Innovations in Intelligence Systems

Digital innovations have, in recent decades, reshaped paradigms within intelligence decision-making systems (Lombardi & Vannuccini, 2021). Traditional intelligence

systems relied on manual data collection, human analysis, and decision-making through hierarchical structures. With the emergence and development of information and communication technologies (ICT), high-performance computing, the Internet of Things (IoT), and big data, the intelligence decision-making process has expanded and accelerated (Ali et al., 2024). The advent of technologies such as real-time analytics, automated multi-source data collection, and the application of machine learning algorithms has enabled a shift from reactive to proactive and predictive intelligence processes. For instance, research on enterprise digital intelligence indicates that the transformation of “digitally intelligent” enterprises involves connecting the external environment and users through data, networks, and smart technologies (Liu & Song, 2024). Bibliometric reviews of digital innovations demonstrate a growing research trend and identify dimensions such as antecedents, execution, outcomes, and levels of digital innovation (Manotti et al., 2020). In the intelligence context, this implies that technologies enabling digital transformation – software, sensors, connectivity, and algorithms – become essential for generating and utilizing information for decision making. The development of digital technologies has impacted not only the technical platform but also organizational processes and culture: intelligence agencies and systems must integrate interdisciplinary approaches, ranging from data engineers and analysts to strategic managers. Furthermore, the increased complexity and heterogeneity of data sources (e.g., satellite imagery, signals, social media, and network streams) require new models of management and analysis.

Digital transformation in intelligence systems can be conceptualized through three stages: data collection, processing/transformation, and analysis for decision-making (Han et al., 2025). Digital technologies enable automated, continuous, and large-scale data collection from diverse sources. IoT sensors, drones, satellite sensors, network logs, social media, and other digital traces present significant potential for intelligence systems. These innovations allow for much greater speed and variety in data collection compared to previous manual methods. The vast volumes of raw data require efficient methods for cleaning, integration, aggregation, and transformation into a format suitable for analysis (Dhawas et al., 2024). In this context, data management platforms and ETL (Extract, Transform, Load) processes play a crucial role. Investments in digital infrastructure allow intelligence systems to operate in real-time or near-real-time. At this level, technologies such as big data analytics, machine learning algorithms, data visualization, and decision support systems enable the transformation of data into knowledge and action. A study by Kowalski (2023) demonstrates that the combination of AI and analytics significantly improves both accuracy and decision-making speed, while also identifying barriers such as data integration, algorithmic bias, and system interoperability. In the intelligence context, this means that digital transformation facilitates better connectivity between data sources and analytical models, a shift from reactive

procedures (post-incident) to predictive and preventive ones, and greater efficiency in resource allocation and timely decision-making.

Automation in intelligence systems involves the use of software agents, algorithms, and robots to collect, filter, and analyze information with minimal or no human intervention (Heer, 2019). Automation accelerates the data collection process and reduces human error but also introduces new challenges – ensuring that automated processes correctly interpret and classify data, handling misinformation, and integrating human oversight within automated systems. Big data represents the concept and practice of working with extremely large, complex, and heterogeneous datasets that exceed the capabilities of traditional processing methods (Rao et al., 2019). In intelligence systems, big data sources include network signals, satellite data, social media data, telecommunications streams, IoT sensors, and similar sources. Analyzing such data can reveal patterns, anomalies, and trends that human analysts could not detect using traditional techniques. For example, Almanasra (2024) shows that integrating AI and big data technologies leads to significant improvements in efficiency, accuracy, and security. In this context, analytics refers to a set of techniques that allow the interpretation of collected and processed data for decision-making purposes (Sarker, 2021). Analytics can be divided into three layers: descriptive (what happened), predictive (what might happen), and prescriptive (what should be done). In intelligence systems, predictive and prescriptive analytics are particularly important because they enable threat anticipation, scenario simulation, and actionable recommendations. Digital innovations allow analytics to operate in near real-time, with automated models that continuously improve through machine learning.

Automation, big data, and analytics are not isolated phenomena – they complement each other. Automated systems collect large amounts of data, big data infrastructure enables storage and management of these data, and analytics (combined with machine learning) transforms it into actionable insights (Alaassar et al., 2025). The literature on digital innovations highlights that "data-driven operation, instant release, and swift transformation" serve as mechanisms for the rapid scaling of digital innovations (Manotti et al., 2020).

3. Machine Learning in the Context of Intelligence Decision-Making

Machine learning (ML) is a subfield of artificial intelligence that enables systems to learn from data, recognize patterns, and make predictions without explicitly programming all rules (Taye, 2023). In intelligence decision-making, ML can support the processes of selection, classification, and prediction of large volumes of heterogeneous data, which is particularly relevant for high-risk and uncertain systems. A study conducted by Salem et al. (2024) demonstrates that the application of ML algorithms can significantly enhance the rationality of decision-making in public administration and e-governance. The most important aspects include automatic extraction of meaning from data, accelerated processing, and scalability in complex systems. In intelligence systems, the theoretical foundations of ML approaches include:

- modeling input data (supervised or unsupervised) originating from diverse sensors, signals, and communications,
- constructing and training algorithms that optimize a target function (e.g., threat classification, anomaly detection, risk prediction),
- performance evaluation (accuracy, recall, precision, F-measure) and interpreting results in the context of decision-making,
- integration with decision support systems, where ML models serve as tools for generating options, alerts, or predictions for human analysts (Salem et al., 2024).

A study by Merkert et al. (2015) indicates that the usefulness of ML algorithms for decision support systems depends on the task and the stage of the decision-making process in which they are applied. Table 1 provides an overview of algorithm types. The application of different algorithm types allows intelligence decision-making systems to respond flexibly to various challenges – supervised learning for known scenarios, unsupervised learning for discovering unforeseen patterns, and deep learning for complex multimedia sources.

Table 1: Types of Algorithms (Supervised, Unsupervised, Deep Learning)

Category	Description	Examples of Application in Intelligence Decision Making
Supervised Learning	Algorithms trained on labeled data (input-output), aiming at prediction or classification.	Classification of communications as security threat or not, prediction of attack risks.
Unsupervised Learning	Algorithms that identify structure in data without pre-defined labels (e.g., clustering, dimensionality reduction).	Detection of unknown communication clusters or anomalous patterns indicating security threats.

Deep Learning	Multi-layer neural models capable of processing complex, high dimensional data (e.g., images, signals, text).	Processing satellite imagery, video materials, social network analysis for intelligence purposes.

Source: (Naeem et al., 2023)

In intelligence systems, ML technologies provide the following contributions (Rao et al., 2024):

- Automation of the analysis of large volumes of data from diverse sources (satellite imagery, IoT sensors, telecommunication flows, social media).
- More precise identification of risks and threats through advanced scenario prediction modeling.
- Faster response due to algorithmic processing and generation of alerts in real or near-real time.
- Support for analysts through systems that suggest actions, describe scenarios, and prioritize tasks.

Salem et al. (2024) confirm that ML positively affects decision-making rationality in the public sector – the application of supervised and unsupervised learning significantly increases efficiency and speed. Furthermore, Ali et al. (2023) highlight the integration of ML with multi-criteria decision-making methods as "intelligent decision support systems". In the intelligence context, the application of machine learning faces a number of specific challenges. One issue is the heterogeneity and high dimensionality of data, as intelligence systems collect information from diverse sources and in different formats, requiring rapid and efficient data integration. Additionally, models must be capable of detecting unknown situations, so-called zero-day threats, i.e., patterns that have not been previously identified, and not only known threats. A particular challenge is the tendency of deep models to operate as "black boxes," which reduces transparency and interpretability, whereas auditability is critical in intelligence systems (Matthew, 2025). Ethical considerations, privacy, and user trust also play a significant role, as research shows that trust in algorithmic decisions greatly affects technology adoption (Ghasemaghaei & Kordzadeh, 2025). Finally, the integration of machine learning with human decision-making presents an additional challenge – the model and the analyst must be coordinated so that the human factor remains in the loop, as insufficient synergy can lead to misinterpretations or excessive automation.

ML represents a significant component of digital innovations in intelligence systems. Understanding its theoretical foundations, properly applying the appropriate algorithm types, and being aware of the challenges allows ML models to be used as tools in intelligence decision-making systems, but not as replacements for human analysis.

4. Review of Relevant Research

Research on the application of ML in decision-making systems has been rapidly increasing. For example, Lai et al. (2021) analyzed over 100 empirical studies on human-AI collaboration in decision-making, highlighting gaps within three dimensions – decision-making tasks, AI models, and supporting elements, along with evaluation metrics. Furthermore, Mohamed (2023) emphasizes how deep learning redefines the analytical capabilities of organizations for decision-making, pointing to the interdisciplinarity and the connection between strategic approaches and data presentation. Vourganas and Michala (2024) conclude that qualitative and quantitative challenges in data limit the full effectiveness of ML models in detection and prevention. Emerging trends include:

- A shift from isolated models to hybrid systems where ML is integrated with human decision-making.
- A focus on transparency and explainability as a response to the need for auditability (Mohseni et al., 2021).
- Increased attention to the security risks of ML systems, which directly affect their usability in intelligence domains (Paracha et al., 2024).
- Discussion on the structure and dynamics of human-machine relationships in decision-making, rather than solely on technical implementation.

Table 2: Models and Their Applications in Decision-Making Domains

Approach/Mod el	Application in Decision Making Domains	Specifics and Notes
ML + MCDM Integration	Analysis and ranking of options in complex decision-making systems	Co mbination of predictive ML models and multi-criteria decision-making (MCDM)analytical methods (Ali et al., 2023)
Human-in-the Loop Hybrid	Inclusion of the human factor in ML decision making processes	Wang et al. (2022) highlight gaps in the literature
Explainable AI (XAI) Models	Critical when decision transparency is required (e.g., intelligence systems)	Multidisciplinary review emphasizes the importance of design and evaluation of XAI systems (Mohseni et al., 2021)

Robust/Adversarial-Resistant Models	When the system is exposed to adversarial attacks (e.g., cybersecurity)	Kawamoto et al. (2023) provide a review classifying vulnerabilities

Source: (author)

The review provided by Ali et al. (2023) reveals that ML algorithms are most frequently applied alongside multi-criteria decision-making (MCDM) methods in complex decision-making problems. Table 2 presents several models/approaches mentioned in the literature, along with their specific applications in decision-making contexts. The literature indicates that the most effective approaches in intelligence decision-making combine relevant data, tailored algorithms, human oversight, and mechanisms for assessing model risk and bias.

Although the application of ML in decision-making systems offers significant advantages, the literature highlights extensive limitations and challenges:

- Data quality and quantity are often insufficient. Reviews on ML in cybersecurity emphasize that the diversity and heterogeneity of data sources, inconsistency of features, and lack of standardized datasets limit model validity (Shaukat et al., 2020).
- Model bias and interpretability: Without adequate human oversight and understanding, ML decisions can be unreliable in critical systems. Research on XAI and human-in-the-loop approaches indicates that existing studies insufficiently address how users (analysts, decision-makers) understand and apply ML outputs (Mohseni et al., 2021).
- Security risks of ML systems: Model attacks, data theft, and manipulation of model training represent real threats, especially in intelligence systems that rely on confidential information (Blauth et al., 2022).
- Generalization and applicability in specialized domains: Many studies come from commercial or industrial domains and are difficult to directly translate to highly specialized scenarios, such as intelligence systems, where conditions, pressures, and risks differ (Perez-Cerrolaza et al., 2024).
- Ethical and regulatory barriers: Integrating ML models into systems that affect national security, strategic decision-making, or risk management must consider ethics, legislation, and accountability, which the literature often identifies as underdeveloped areas (Montasari, 2024).

While the literature provides rich insights and evidence on the effects of ML in decision making processes, its application in intelligence systems requires further adaptation and research – particularly regarding the human factor, system security, and domain-specific requirements.

5. Challenges, Innovations, and Future Directions of Machine Learning Application in Intelligence Systems

The application of machine learning (ML) in intelligence systems faces multiple layers of challenges. Technical challenges include data heterogeneity, high dimensionality, and the need for fast real-time processing. Models often require large datasets for training, while access to high-quality and reliable data is limited in intelligence contexts. Ethical challenges relate to privacy, transparency, and accountability in decision-making. Algorithmic decisions can be biased or non-explainable, potentially leading to incorrect risk assessments or inadequate operational responses (Hotko, 2024). Security challenges involve vulnerabilities of ML models to attacks, data manipulation, and leakage of sensitive information, which are critical in the intelligence sector.

Research trends indicate the development of hybrid systems in which machine learning operates in coordination with human analysts, enabling "human-in-the-loop" decision making models (Kumar et al., 2024). Further development focuses on increasing model explainability (XAI), robustness against attacks, and the ability to adapt to new, unknown threats.

The integration of ML with other technologies opens additional opportunities. Combining ML with artificial intelligence allows advanced analysis and prediction; blockchain can provide secure and transparent data records, reducing the risk of manipulation; quantum analytics potentially enables faster processing of complex and high-dimensional data, which is strategically important in intelligence decision-making.

The perspective for ML development in intelligence systems is oriented toward secure, explainable, and adaptive application, in synergy with advanced digital technologies and human oversight.

6. Conclusion

Digital innovations and the application of machine learning (ML) significantly transform intelligence decision-making systems, changing the ways information is collected, processed, and interpreted. A review of the literature and analyzed application examples show that automation, big data, and analytics, combined with ML algorithms, enable more precise threat identification, faster data processing, and enhanced decision-making in real or near-real time. Machine learning allows for scalability and adaptability of systems, while different algorithmic approaches – supervised, unsupervised, and deep learning – address various types of challenges, ranging from routine scenarios to complex, multimedia, and previously unknown threats.

At the same time, the application of ML in intelligence systems faces multi-layered challenges. Technical challenges include data heterogeneity, high dimensionality, and the need for real-time processing, while ethical and security challenges encompass transparency, algorithmic bias, privacy protection, and vulnerability to attacks. The human factor remains crucial for interpreting and evaluating ML model outputs, highlighting the need for a "human-in-the-loop" approach and the integration of explainable AI (XAI) models into intelligence processes.

A review of current research indicates that the most effective approaches combine algorithmic automation, multi-criteria decision analysis methods, human oversight, and mechanisms for controlling model risks and biases. Future development directions focus on hybrid systems, increased explainability, robustness, and adaptability of models, as well as integration with other digital technologies such as blockchain and quantum analytics, enabling safer and more efficient processing of large and heterogeneous datasets.

Machine learning represents a key component of digital innovations in intelligence systems, not as a replacement for human analysis, but as a tool to enhance the accuracy, speed, and quality of decision-making. Its effective application depends on balancing technological capabilities with human oversight, security, and ethical standards, enabling intelligence organizations to achieve sustainable efficiency and resilience in a dynamic and complex digital environment.

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Ključni faktori i indikatori zadovoljstva poslodavaca u implementaciji dualnog modela studija u visokom obrazovanju u Srbiji

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Apstrakt: Dualni model studija u visokom obrazovanju u Srbiji razvijen je kao mehanizam jačeg povezivanja visokoškolskih ustanova i tržišta rada, kroz integraciju akademskog učenja i učenja kroz rad kod poslodavca.
Cilj rada je da prikaže nivo zadovoljstva poslodavaca koji učestvuju u implementaciji ovog modela, identifikuje percipirane benefite i izazove i predloži smernice za unapređenje. Rezultati su prikazani kroz studiju slučaja na Akademiji strukovnih studija Politehnika, Beograd, Republika Srbija, visokoškolskoj ustanovi sa 22 akreditovana studijska programa po dualnom modelu. Istraživanje je sprovedeno na uzorku 22 kompanije, prevashodno iz industrijsko proizvodnog sektora i segmenta malih preduzeća, putem strukturiranog upitnika koji je obuhvatio kvantitativna i kvalitativna pitanja. Na osnovu analize podataka uočava se visok nivo zadovoljstva poslodavaca saradnjom sa visokoškolskom ustanovom i organizacijom učenja kroz rad, kao i to da većina učesnika smatra da su njihova inicijalna očekivanja delimično ili u potpunosti ispunjena. Poslodavci posebno ističu da studenti koji studiraju po dualnom modelu studija poseduju razvijenija praktična znanja, radne navike i spremnost za rad u realnom poslovnom okruženju u poređenju sa tradicionalnim diplomcima. Kao glavni izazovi identifikovani su usklađivanje akademskog i poslovnog kalendara, opterećenje mentora i administrativne procedure.
Dualni model studija ima značajan potencijal za unapređenje zapošljivosti diplomiranih studenata i uvećanje kvaliteta visokog obrazovanja. Takođe, rezultati istraživanja pokazuju da je za razvoj ovog modela obrazovanja potrebno dalje sektorsko širenje i institucionalno jačanje.

Ključne reči: dualni model studija, visoko obrazovanje, poslodavci, zapošljivost, učenje kroz rad.

Key Factors and Indicators of Employer Satisfaction in the Implementation of the Dual Study Model in Higher Education in Serbia

Abstract: The dual study model in higher education in Serbia was developed as a mechanism to strengthen the connection between higher education institutions (HEIs) and the labour market by integrating academic and work-based learning (WBL) on employers' premises. This paper aims to present the level of satisfaction among employers participating in this model, identify perceived benefits and challenges, and propose guidelines for improvement. The results are presented through a case study of the Academy of Applied Studies Polytechnic, Belgrade, Republic of Serbia—an HEI with 22 accredited dual study programs. The research was conducted on a sample of 22 companies, primarily from the industrial-manufacturing sector and the small business segment, using a structured questionnaire that included both quantitative and qualitative questions. Data analysis reveals a high level of employer satisfaction regarding cooperation with the HEI and the organization of work-based learning; most participants consider their initial expectations to be partially or fully met. Employers specifically highlight

that dual-model students possess more developed practical knowledge, work habits, and readiness for a real business environment compared to traditional graduates. Key identified challenges include aligning the academic and business calendars, mentor workload, and administrative procedures.
The dual study model offers substantial potential to advance graduate employability and elevate pedagogical standards in higher education. The findings from this case study suggest that the continued evolution of this framework may benefit from broader integration across various industries and education sectors, as well as more robust institutional capacity building.

Keywords: dual study model, higher education, employers, employability, work-based learning.

1. Introduction

The dual study model in higher education connects HEIs with the labour market by integrating theory with practice. This model responds efficiently to economic needs, technological change, and the demand for new skills. It aims to increase graduate employability, boost economic competitiveness, and support sustainable human resource development amid ongoing change. By creating a system where qualifications reflect acquired competencies, this education model raises the quality of knowledge and skills. For employers, it helps ensure a steady supply of personnel. This widely recognized approach closely aligns educational outcomes with labour-market needs and narrows the gap between theoretical and practical knowledge (Göhringer, 2002; Pogátsnik, 2021).

In the Republic of Serbia, improving the connection between the education system and the economy is recognized as a key challenge in higher education development. The business sector has repeatedly highlighted the shortage of adequately trained experts. It also emphasizes the need for graduates to gain higher levels of practical knowledge and work experience during their studies. As a result, the dual study model was introduced to enable more direct cooperation between HEIs and employers. It also aims to help students acquire practical competencies in a real work environment. Previous research shows that employers often express dissatisfaction with graduates' practical competencies. These findings underscore the need for stronger integration of work-based learning into higher education systems (Janovac et al., 2020).

To institutionalize this model, the Republic of Serbia adopted the Law on the Dual Model of Studies in Higher Education. It was published in the *Official Gazette of the Republic of Serbia* No. 66/2019. This law regulates the content and manner of implementing dual studies. It covers the mutual rights and obligations of students, HEIs, and employers, as well as students' material and financial security. Other relevant matters for the dual model's realization are also included. Although this is a relatively new form in higher education, it is gaining visibility and acceptance, especially in technical and manufacturing activities. According to the Office for Dual Education and the National Qualifications Framework, 12 HEIs in Serbia implement dual study programs. This includes 3 faculties/academic studies and 9 academies of applied studies, showing slower implementation within academic studies.

2. Theoretical Framework

HEIs operate amid globalization, technological change, and rising demand for practical knowledge (Boer et al., 2002; Ertl, 2020). Traditional study models often face criticism for weak economic links and slow adaptation to changing job requirements (Janovac et al., 2020; Pogatsnik, 2018). Industry representatives say these gaps mean graduates are not always ready for immediate integration into work (Buchynska et al., 2020).

The dual study model combines instruction at the HEI with work-based learning at the employer. Practical training is an integral part of the study program and carries ECTS credits. This aligns learning outcomes, qualification standards, and organizational needs. It also positions employers as active partners in the educational process (Göhringer, 2002; Pogátsnik, 2021). Research confirms that the dual model efficiently adapts competencies to modern labor market demands (Bolli et al., 2021; Pogátsnik, 2021).

Experiences from countries with a long tradition of dual education, such as Germany, Austria, and Switzerland, show that this model reduces youth unemployment, shortens the transition from study to work, and strengthens productivity (Ertl, 2020; Maier, 2022). In these countries, the dual model is a recognizable system that significantly boosts organizational productivity. Maier (2022) notes that dual higher education in Germany is an attractive alternative for young people, especially as programs expand and awareness grows. Studies in Hungary,

Ukraine, and Kazakhstan also indicate benefits for students, SMEs, the economy, and society. However, these studies also highlight challenges (Kocsis & Pusztai, 2021; Kravchenko et al., 2023).

Furthermore, implementing dual study models requires strong institutional coordination, clearly defined stakeholder roles, and ongoing curriculum updates to technological and economic shifts (Hesser, 2018; Muhambetaliev & Kasymova, 2016). The success of this model depends primarily on the quality of collaboration between higher education institutions and employers, as well as on organizations' ability to provide appropriate mentoring and learning conditions in real-world settings. Despite many benefits, research also identifies challenges such as administrative complexity, resource limitations, and the need for systematic support from public institutions, all of which are crucial to the long-term viability of the dual study model.

3. Aim and Research Questions

To assess the dual model's success in practice, this paper presents a case study of the Academy of Applied Studies Polytechnic, the first HEI in Serbia to implement the dual study model. Starting with 12 accredited dual programs in 2020, the Academy now has 22 (an 83.3% increase), reflecting the growing needs of the economy and increasing interest from students and employers. The paper aims to analyze employer satisfaction, identify benefits and challenges, and provide recommendations for improvement.

4. Methodology

This study applies a mixed-methods research approach, combining quantitative and qualitative methods to provide a comprehensive assessment of employer satisfaction with the implementation of the dual study model in higher education. The quantitative component focuses on measuring satisfaction and identifying key factors influencing the model's implementation. At the same time, the qualitative approach provides a deeper understanding of the perceptions, challenges, and limitations employers face. The study has a descriptive-analytical character, with elements of an exploratory approach, given the relatively recent introduction of the dual study model in higher education in the Republic of Serbia.

The research sample consists of 22 companies that participate or plan to participate in the implementation of the dual study model in cooperation with the Academy of Applied Studies Polytechnic. A purposive sampling strategy was applied, including companies that have formalized cooperation with higher education institutions, participate in work-based learning processes, and have experience in working with students within the dual study model. The sample structure indicates a predominance of companies from the industrial and manufacturing sectors, small and medium-sized enterprises, and respondents holding managerial positions with significant professional experience. Such a sample structure ensures the relevance of the findings but also limits their broader generalizability.

A structured survey questionnaire, specifically designed for this research, was used to collect data. The questionnaire consisted of several thematic sections, including general characteristics of companies and respondents, experience with the dual study model, satisfaction with its implementation, perceptions of benefits and challenges, and attitudes toward the visibility of and institutional support for this educational model. Key variables were operationalized using a set of indicators measured on a Likert scale (1–5), enabling quantitative analysis and comparisons of the data. In addition to closed-ended questions, the questionnaire included open-ended questions to capture additional qualitative insights.

Data was collected via a survey, with questionnaires distributed to companies involved in the dual study model. The research was conducted under conditions that ensured respondents' anonymity and confidentiality, thereby reducing response bias and increasing the reliability of the collected data. In addition to primary data, the study also relied on the analysis of relevant documents, including the legal and strategic framework, which contributed to a broader understanding of the research context.

The study analyses key variables related to employer satisfaction, perceptions of student competencies, perceived benefits of the dual model, and challenges and limitations in its implementation. Special attention is also given to the visibility of the dual study model and the level of institutional support.

Quantitative data were analyzed using descriptive statistics, including frequency distributions, percentages, and measures of central tendency. The results are presented in tabular and graphical form to facilitate interpretation. Qualitative data were analyzed using thematic (content) analysis, which involves identifying and grouping key themes from respondents’ answers.

To ensure the validity and reliability of the research, particular attention was paid to the clarity of the questionnaire design and the consistency of the measurement instruments. Although formal reliability testing was not the primary focus, the instrument was based on established practices in similar empirical studies, ensuring content validity and internal coherence.

Despite its contributions, the study has certain limitations. In particular, the relatively small sample size and the dominance of specific sectors limit the generalizability of the findings. Additionally, reliance on self-reported data introduces the possibility of subjective bias. Nevertheless, the results provide valuable empirical insights into the implementation of the dual study model and serve as a basis for further research and improvement of practice.

5. Results

A significant proportion of companies are already actively implementing dual study programs, while others are in the process of adopting the dual study model.

The statistics of the distribution of respondents by sectors of activity are presented in Table 1. Out of the total number of respondents, only one company selected two sectors.

Table 1:Distribution of respondents by sector of activity

Sector	Number of respondents	Percentage (%)
IT and Software Engineering	0	0
Industry and Manufacturing	15	68.18
Trade and Services	5	22.73
Healthcare	0	0
Finance and Banking	0	0
Education	0	0
Other	3	13.64

*Note: Total count is 23 as one company selected two sectors.

Most respondents (68.18%) come from the industry and manufacturing sectors, indicating that the sample primarily focuses on technical and production-related activities. The trade and services sector accounts for 22.73% of respondents, while the “Other” category accounts for 13.64%, indicating fewer respondents from non-standard or mixed sectors.

Table 2: Distribution of respondents by number of employees

Company size	Number of respondents	Percentage (%)
Micro (up to 10 employees)	0	0
Small (11–50 employees)	15	68.18
Medium (51–250 employees)	5	22.73
Large (more than 250 employees)	0	0

The sample structure by company size indicates a predominance of respondents from small enterprises (68.18%), suggesting that the research findings are most representative of this segment of the economy. Medium-sized enterprises account for 22.73% of the sample, while micro and large companies are not represented.

Table 3: Statistics of respondent distribution by positions in the company

Position	Number of Respondents	Percentage (%)
HR	4	18.18
Manager / Lead	14	63.64
Engineer	3	13.64
Not specified	2	9.09

The results indicate that most respondents are managers (63.64%), suggesting that the sample is composed primarily of managers. A much smaller percentage are in HR roles (18.18%) and engineers (13.64%), while 9.09% of respondents did not specify their position.

Table 4: Statistics of respondent distribution by years of work experience in the industry

Years of Experience Interval	Number of Respondents	Percentage (%)
0–5	4	18.18
6–10	0	0
11–20	7	31.82
21–30	10	45.45
>30	1	4.55

The analysis shows that most respondents fall within the 21–30 years of experience range (45.45%), suggesting that the sample mainly consists of highly experienced professionals. A notable portion of respondents is also in the 11–20 years range (31.82%), further confirming the mature and experienced makeup of the sample.

5.1. Experience in Implementing Dual Study Model

Statistics of respondent participation in the dual study model:

Table 5: Statistics of respondent distribution based on participation in the implementation of the dual study model

Interval (years)	Number of Respondents	Percentage (%)
0	4	18.18
1–2	4	18.18
3–4	9	40.91
5+	5	22.73

This distribution indicates that Serbia's dual study model is currently in a stable growth phase, primarily led by companies with moderate experience and stable prospects for ongoing institutional and systemic development.

The statistics of respondent distribution based on the motives for participating in the implementation of dual education are as follows:

Table 6: Statistics of respondent distribution based on the motives for participating in the implementation of dual education

Motive	Number of Respondents	Percentage (%)
Need for staff with practical knowledge	15	68.18
Ability to train future employees ourselves	12	54.55
Improving the quality of cooperation with higher education institutions	4	18.18
Incentives and support from the state/institutions	0	0
Recognized social responsibility and support for education	9	40.91
Desire to participate in achieving the competencies of future experts	4	18.18
Positive experiences of other organizations	1	4.55
Internal strategic human resources development	3	13.64
Other	0	0

The results show that the most significant motive for adopting the dual study model is the need for staff with practical knowledge (68.18%), indicating that companies primarily view the dual model as a means to improve the quality of the future workforce. A high percentage of respondents (54.55%) also cite the ability to shape and train future employees independently, further confirming a strategic orientation toward long-term human resource development.

Question: To what extent have expectations been met so far?

Table 7: Statistics of respondent distribution based on the fulfillment of expectations from participation in the implementation of the dual study model

Fulfillment Rating	Number of Respondents	Percentage (%)
Fully met	7	31.82
Partially met	11	50
Not met	0	0
Cannot assess yet	3	13.64
Other	1	4.55

The results indicate that most organizations believe their expectations from the dual study model are partially met (50%), while nearly a third of respondents (31.82%) feel their expectations are fully met. A notable absence of negative responses regarding the fulfillment of participants' expectations was observed.Analysis of these results shows a generally positive reception; notably, no respondents reported that their expectations were "not met." Half of the participants feel their expectations have been partially fulfilled, while nearly a third report full satisfaction.

Table 8: Statistics of respondent distribution based on satisfaction with the organization of work-based learning

Indicator	Average Rating
Calendar alignment	3.77
Schedule organization	4
Definition of responsibilities	3.95
General coordination	4.05
Overall satisfaction index	3.94

The results show that respondents are overall satisfied with the organization of the work-based learning program, with an overall satisfaction index of 3.94. The highest rating was given to the program's general coordination, indicating that cooperation among all actors is successfully implemented in most cases.

Statistics of respondent distribution based on satisfaction with the quality of the curriculum.

Table 9: Statistics of respondent distribution based on satisfaction with the quality of the curriculum

Indicator	Average Rating
Program content and practice	3.82
Program relevance	3.73
Cooperation with the institution	3.86
Relationship between theory and practice	3.64
Overall satisfaction index	3.76

The results indicate that respondents are generally moderately satisfied with the organization of the work-based learning program, with an overall satisfaction index of 3.76. The highest rating was given to cooperation with the higher education institution.

Satisfaction with student preparedness for the work environment:

Table 10: Statistics of respondent distribution based on satisfaction with student preparedness for the work environment

Indicator	Average Rating
Theoretical preparedness	3.59
Motivation and interest	3.59
Adapting to the environment	3.68
Work habits and behavior	3.59
Overall satisfaction index	3.61

The results show that respondents are moderately satisfied with students' preparedness for the work environment, with an overall satisfaction index of 3.61.

Satisfaction with administrative procedures:

Table 11: Statistics of respondent distribution based on satisfaction with administrative procedures

Indicator	Average Rating
Administrative workload	3.65
Efficiency of procedures	3.26
Documentation management	3.74
Institutional support	3.65
Overall satisfaction index	3.58

The results show that organizations are moderately satisfied with the administrative procedures for implementing the dual study model, with an overall satisfaction index of 3.58. The highest average rating was given to documentation and reporting, indicating that this segment is relatively well-organized and functional. The scope of administrative obligations and institutional support was rated stable, but not high, suggesting a sense of burden and a need for further improvement in communication with competent bodies.

Satisfaction with support from state institutions

Table 12: Statistics of respondent distribution based on satisfaction with support from state institutions

Indicator	Average Rating
Institutional support	3.43
Regulatory alignment	3.3
Availability of information	3.65
Financial incentives	3.04
Overall satisfaction index	3.36

Question: Which challenges did you experience most frequently?

Table 13: Statistics of respondent distribution based on identified challenges

Challenge	Number of respondents	Percentage (%)
Insufficient student preparedness for working in a real environment	8	36.36
Lack of time or resources for mentoring	10	45.45
Insufficient cooperation with higher education institutions	1	4.55
Mismatch between the academic program and employer needs	3	13.64

Complex administrative procedure/bureaucracy in the accreditation process of the dual study model in higher education	9	40.91
Lack of internal support within the organization	0	0
Financial costs of participating in the dual study model in higher education	4	18.18
Insufficient information about rights and obligations in the dual education system	6	27.27
Low flexibility in program adjustment	2	9.09
Other challenges	0	0

The results show that the biggest challenge for organizations is the lack of time and resources for mentoring efforts, highlighting a significant burden on current human resource capacities. This is followed by complex administrative procedures, emphasizing that bureaucratic requirements are a major barrier to wider adoption of the dual study model. Satisfaction with collaboration with higher education institutions is generally high.

6. Discussion

Overall, the results indicate that the main obstacles to the development of the dual study model are systemic and organizational, rather than internal weaknesses of the companies themselves, which confirms the need for simplified procedures, stronger institutional support, and better structuring of the mentoring system.

The dual study model in the Republic of Serbia serves as a strategic tool that allows employers to actively engage in workforce education, directly shape curricula, and identify talent early. Although employers are generally satisfied (average rating 3.94) and consider students from this model to be better prepared for work than traditional graduates, up to 50% of respondents report that their expectations have been only partially met due to existing structural barriers. Similar findings are seen in other studies, which emphasize that the success of dual education largely depends on the level of institutional coordination and the resources available within participating organizations (Hesser, 2018; Muhambetaliev & Kasymova, 2016). To provide a broader comparative perspective, it is important to note that the outcomes observed in Serbia are generally consistent with findings from countries with well-established dual education systems, such as Germany and Austria, where strong links between education and the labour market contribute to higher employability and smoother school-to-work transitions (Ertl, 2020; Maier, 2022). However, unlike these systems, which are characterized by long-standing institutional support and extensive employer participation, the Serbian model is still in an earlier stage of development. As a result, while qualitative benefits appear comparable, quantitative indicators—such as employment rates and productivity gains—are less systematically monitored and require further empirical validation.

The current implementation of the model is uneven: it dominates in industry (68.18%), while sectors such as IT, finance, and healthcare are completely absent. The findings of this study have important policy implications for both government institutions and higher education providers. To overcome the identified challenges, it is necessary to develop targeted policy measures that support employer participation, reduce administrative barriers, and enhance the quality of work-based learning. This includes introducing financial incentives, standardizing mentoring systems, and strengthening institutional cooperation mechanisms. Without such coordinated policy interventions, the full potential of the dual study model may remain underutilized.

This points to the need for greater flexibility and adaptation of the model to the specifics of office and digital business operations, rather than just manufacturing activities.

The main challenges faced by employers are of a managerial and organizational nature:

- Lack of resources for mentorship: Nearly 45.5% of companies, especially small ones, struggle to balance production processes with their educational role.
- Administrative burden: A high perception of bureaucracy (40.91%) and lower ratings for procedural efficiency call for urgent simplification and digitization of communication with faculties.
- Management issues: Overburdened mentors, a limited number of hours for work-based learning, and challenges in coordinating schedules

To encourage greater economic involvement, the introduction of financial incentives and state subsidies, following the Austrian model, is proposed (BliemW., Petanovitsch,A.,Schmid, K.2014.; Cedefop

2026.;Dornmayr, H. 2024; Federal Ministry of Finance (BMF)2025; Federal Ministry of Labour and Economy (BMAW)2022, 2024; WAFF 2026.)

Specific proposals include:

1. Tax incentives: Recognition of student education costs and mentor training as tax deductions.
2. Direct subsidies: Payment of state aid per student, which would be highest at the beginning (equivalent to three monthly allowances in the first year), and then progressively decrease (to two in the second and one in the third year) as student productivity grows.
3. Quality support: Additional financial resources for the professional development of mentors and improving the quality of the training itself.

Further development of the system must focus on sectoral diversification, strengthening state support, and clarifying norms to create more sustainable and functional models of cooperation between science and industry.

Furthermore, it is important to note that the effectiveness of the dual study model is not solely determined by structural and institutional factors, but also by how well academic curricula align with rapidly changing industry demands. In an era of accelerated technological progress and digital transformation, higher education institutions face growing pressure to update study programs and adopt innovative teaching methods regularly. In this context, the dual model can act as a flexible mechanism for knowledge transfer and real-time skills adjustment; however, its success relies on the adaptability of curricula and the responsiveness of both educational institutions and employers (Ertl, 2020; Pogátsnik, 2021).

Additionally, the findings of this research suggest that small and medium-sized enterprises, which dominate the sample, may face greater challenges in providing adequate mentoring and organizational support compared to larger companies with more developed human resource capacities. This indicates the need for differentiated policy measures and support mechanisms tailored to the specific needs of different types of organizations. Strengthening institutional support, particularly through mentor training programs and simplified administrative procedures, could significantly improve the overall effectiveness and scalability of the dual study model. Despite the valuable insights this study provides, several methodological limitations should be acknowledged. The relatively small sample size and the predominance of companies from the industrial and manufacturing sector may limit the generalizability of the findings to other sectors, particularly knowledge-intensive industries. In addition, the sample is largely composed of small and medium-sized enterprises, which may face different challenges than larger organizations. These factors suggest that the results should be interpreted with caution and highlight the need for future research using larger, more diverse samples. Another important aspect that requires further investigation is the long-term impact of the dual study model on graduates' career development. While existing research and employer perceptions suggest that dual students are better prepared for immediate employment, there is still limited longitudinal evidence on their long-term career progression, income levels, and professional advancement compared to graduates of traditional study programs. Addressing this gap would provide a more comprehensive evaluation of the dual model's overall effectiveness.

To provide broader context for the reported employer satisfaction, it is useful to note that literature generally indicates a positive student perception of the dual study model. Research suggests that students value the opportunity to gain professional expertise and familiarize themselves with real business environments, thereby enhancing their employability prospects (Kocsis & Pusztai, 2021)

Such work-based experiences are recognized as 'authentic' learning environments that facilitate the development of professional identity

However, the dual study model also presents certain challenges from the student perspective. These include the increased workload from simultaneously fulfilling academic and work obligations, potential inconsistencies in the quality of mentoring across companies, and the need to adapt to different organizational contexts. Additionally, students may feel pressure to balance performance expectations across academic and professional settings, which can affect their overall satisfaction and learning outcomes.

Therefore, incorporating the student perspective into future research would provide a more comprehensive understanding of the dual study model, enabling a balanced evaluation of its benefits and limitations from all key stakeholders.

7. Conclusion

The dual study model in Serbia is currently in a phase of stable growth and represents a strategic instrument for aligning education with the real needs of the labour market. Its core value lies in developing personnel with practical competencies directly applicable in the work environment, which is why these students are perceived as better prepared for the workplace than those completing traditional programs.

Although employers express satisfaction with their cooperation with higher education institutions, their expectations have been only partially fulfilled to date. The main obstacles to further development are not only organizational but also stem from the fact that higher education institutions have primarily initiated the system, while adequate institutional and systemic support is still lacking.

To fully integrate this model and boost young people's employability, it is essential to implement the following measures:

- Financial incentives: Introduction of tax breaks for mentorship costs and state subsidies based on the Austrian model, which would cover student stipends during the period when their productivity is still low.
- Mentorship reform: Development of standardized training and official recognition of mentoring work as part of the formal workload, to eliminate resistance caused by overburdening.
- Administrative simplification: Digitization of processes through the introduction of electronic systems for tracking work-based learning and the reduction of bureaucratic procedures during the accreditation process.

Systematically addressing these challenges and expanding the participant base will enable the dual model to become a key factor in raising the quality of higher education in Serbia.

Furthermore, the future development of the dual study model should focus on strengthening institutional collaboration, increasing the flexibility of study programs, and broadening participation across a wider range of economic sectors. This approach would promote a more balanced and inclusive implementation of the model, especially in knowledge-based and service-oriented industries.

Ultimately, the long-term sustainability and effectiveness of the dual study model will depend on the establishment of a stable, supportive policy framework and on continuous collaboration among higher education institutions, employers, and public authorities. Systematic improvement in these areas will position the dual model as a key driver of educational quality, workforce competitiveness, and sustainable economic development in Serbia.

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Liderstvo u inovacionim procesima: Sun i Moon metod kao model održivih inovacija

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Apstrakt: Savremene organizacije se sve češće suočavaju sa izazovom razvoja inovacija koje istovremeno generišu tržišnu vrednost i doprinose društvenom blagostanju. U tom kontekstu, liderstvo ima ključnu ulogu u transformaciji ideja u održive inovacije. Ova studija uvodi i empirijski podržava dualno strukturiran model inovacionog liderstva zasnovan na dva komplementarna pristupa: Sun metod liderstva i Moon metod liderstva. Sun metod naglašava generisanje ideja, eksternu komunikaciju i izgradnju mreža, dok Moon metod stavlja fokus na analitičku evaluaciju, strateško planiranje i strukturiranu implementaciju. Istraživanje kombinuje konceptualni okvir sa empirijskom analizom zasnovanom na uzorku od 1.066 ispitanika iz različitih organizacionih konteksta. Rezultati ukazuju na jasnu funkcionalnu diferencijaciju liderstva, pri čemu eksterno orijentisane uloge favorizuju komunikativno i spolja usmereno liderstvo, dok interno orijentisane uloge naglašavaju analitičko i strukturirano liderstvo. Rezultati dalje ukazuju da se efikasni inovacioni procesi percipiraju kao povezani sa koordinisanom interakcijom oba pristupa, a ne sa njihovom izolovanom primenom. Pored toga, istraživanje identifikuje stabilnu dualnu orijentaciju ishoda, koja ukazuje da se od inovacija dosledno očekuje istovremeno generisanje društvene i ekonomske vrednosti, nezavisno od funkcionalnog konteksta. Studija konceptualizuje inovaciju kao proces strukturiran kroz liderstvo i predlaže dualni model liderstva u kojem se funkcionalno diferencirani pristupi koordiniraju putem zajedničke logike ishoda. Glavni doprinos rada ogleda se u konceptualizaciji inovacionog liderstva kao distribuiranog i ulogama uslovljenog sistema, sugerišući da se usklađivanje diferenciranih liderstvenih uloga i zajedničke orijentacije ka ishodima percipira kao faktor koji podržava održive inovacije.

Ključne reči:: liderstvo; inovacije, inovacioni menadžment, Sun metod, Moon metod

Leadership in Innovation Processes: The Sun and Moon Methods as a Dual Model for Sustainable Innovations

Abstract: Modern organizations increasingly face the challenge of developing innovations that simultaneously generate market value and contribute to societal well-being. In this context, leadership plays a critical role in transforming ideas into sustainable innovations. This study introduces and empirically supports a dual-structured model of innovation leadership based on two complementary approaches: the Sun leadership method and the Moon leadership method. The Sun method emphasizes idea generation, external communication, and network building, while the Moon method focuses on analytical evaluation, strategic planning, and structured implementation. The study combines a conceptual framework with empirical analysis based on a sample of 1,066 respondents across multiple organizational contexts. The findings indicate a clear functional differentiation of leadership approaches, with externally oriented roles favoring communicative and outward-facing leadership, and internally oriented roles emphasizing analytical and structured leadership. The results indicate that effective innovation processes are perceived to be associated with the coordinated interaction of both leadership modes rather than their independent application. In addition, the study identifies a stable dual outcome orientation, indicating that innovations are consistently expected to generate both social and commercial value across functional contexts. The study conceptualizes innovation as a leadership-structured process and proposes a dual leadership model in which functionally differentiated leadership modes are coordinated through a shared outcome logic. The main contribution lies in conceptualizing innovation leadership as a distributed and role-contingent

system, suggesting that the alignment of differentiated leadership roles and shared outcome orientation is perceived to support sustainable innovation.

Keywords: leadership, innovation, innovation management, Sun method, Moon method.

1. Introduction

Innovation is widely recognized as a central driver of organizational competitiveness, yet the internal leadership structures that enable innovation remain insufficiently understood (Schumpeter, 1934; Fatima et al., 2026). Despite its centrality, the process through which ideas evolve into sustainable innovations remains complex and uneven, requiring not only resources and capabilities, but also structured leadership that enables coordination, direction, and implementation (Drucker, 2007; Ignjatović et al., 2023). In this context, leadership is not merely a supportive function, but a constitutive element of innovation processes through which innovation is coordinated, directed, and enacted (Enang et al., 2025). Existing research has extensively examined innovation through the lenses of capabilities, knowledge creation, and organizational processes, emphasizing the need to balance exploratory and exploitative activities (An et al., 2026; Heidenreich et al., 2026). While these perspectives have significantly advanced the understanding of innovation dynamics, they remain largely focused on activities and outcomes, rather than on the internal configuration of leadership roles that support such processes in practice (Felin et al., 2015). In particular, there is a lack of conceptual clarity regarding how different leadership approaches coexist, interact, and distribute across organizational functions during innovation development.

This study addresses this gap by shifting the analytical focus from innovation as a set of activities to innovation as a leadership-structured process, thereby relocating the locus of innovation from activity domains to leadership configurations embedded within organizational roles. While prior research has conceptualized exploration and exploitation primarily at the level of organizational activities and learning processes (March, 1991), the present study operates at a different level of analysis. The Sun and Moon methods do not represent types of activities, but structurally differentiated leadership enactments that are functionally distributed across organizational roles. In this sense, the model does not reproduce the exploration–exploitation distinction, but translates it into a leadership-embedded mechanism. Building on existing theoretical foundations, it develops a leadership-centered interpretation of innovation processes through a dual-structured model of innovation leadership based on two complementary approaches: the Sun leadership method and the Moon leadership method. The Sun method captures a communicative, externally oriented, and initiative-driven form of leadership associated with idea generation, networking, and interaction with the external environment (Rogers, 2003). In contrast, the Moon method represents an internally oriented, analytical, and strategically grounded approach focused on evaluation, planning, and long-term sustainability (Tidd & Bessant, 2018). Together, these approaches reflect the broader need to integrate different forms of knowledge and action within organizations, as emphasized in knowledge creation theory (Nonaka & Takeuchi, 1995).

Beyond leadership differentiation, the study introduces the concept of dual output innovation, which conceptualizes innovation as a process expected to simultaneously generate social and commercial value. This perspective responds to increasing demands for aligning economic performance with societal impact, reinforcing the idea that sustainable innovation requires both market relevance and broader social contribution (Porter & Kramer, 2011; Geissdoerfer et al., 2017). Empirically, the study examines these relationships using data collected from 1,066 respondents across multiple organizational contexts. This design enables a more comprehensive analysis of how leadership approaches are distributed and perceived across different functional roles, providing deeper insight into the structural alignment between leadership practices and organizational activities. The main contribution of this study lies in advancing a theoretically grounded and operationally clear framework that conceptualizes innovation leadership as a structurally distributed and role-contingent system. By empirically demonstrating that leadership approaches are systematically perceived as functionally differentiated, while innovation outcomes remain consistently aligned, the study enhances understanding of how innovation processes are structured, coordinated, and sustained within contemporary organizations. This contribution extends beyond measurement by identifying a structurally consistent pattern linking leadership modes to functional roles, thereby providing an empirically grounded basis for theorizing innovation leadership as a distributed organizational mechanism.

Prior research has primarily conceptualized innovation through activities, capabilities, and processes, while largely overlooking how leadership roles are structurally distributed and coordinated within these processes. This study advances the literature by introducing a leadership-centered framework that differentiates and integrates communicative and analytical leadership roles at the level of organizational structure rather than individual

behavior, thereby reframing innovation as a process enacted through structurally distributed leadership configurations. In doing so, the study enables a more precise understanding of innovation as a process that is not only generated, but structurally organized and sustained through differentiated leadership roles.

2. Literature Review and Hypothesis Development

Innovation has long been recognized as a central driver of organizational and societal development, particularly in the context of competitive advantage and long-term sustainability (Schumpeter, 1934; Porter, 1990). However, the transformation of ideas into sustainable innovations is not an automatic process, but rather a structured and leadership-driven activity that requires coordination, evaluation, and implementation (Drucker, 2007; Tidd & Bessant, 2018). While the Sun and Moon methods draw inspiration from the exploration–exploitation distinction introduced by James G. March (1991), they are analytically distinct and not reducible to it. The key difference lies in the level of analysis, which has been insufficiently addressed in prior research. This distinction is not merely terminological but analytical, as it shifts the focus from what organizations do to how leadership roles are structurally configured to enable such processes. Accordingly, the Sun and Moon methods capture leadership enactments that are embedded in organizational roles rather than interchangeable behavioral modes. This distinction is critical, as it shifts the analytical focus from behavioral flexibility to structural differentiation, positioning leadership not as an individual capability but as an organizationally embedded configuration.

Whereas exploration and exploitation have been predominantly conceptualized as organizational learning processes and activity domains, the present study interprets these logics as functionally embedded leadership configurations. In this sense, the Sun and Moon methods do not represent types of activities, but role-contingent leadership enactments systematically distributed across organizational functions. This shift from activity-based to leadership-embedded differentiation establishes a clear theoretical boundary relative to prior work. Unlike ambidextrous leadership frameworks, such as those proposed by Zacher & Rosing (2015) which emphasize the behavioral flexibility of individual leaders in switching between opening and closing behaviors, the present model does not assume that a single leader performs both functions. Instead, leadership differentiation is structurally distributed across organizational roles, suggesting that innovation processes can be understood as emerging from the coordination of functionally specialized leadership modes rather than from individual ambidexterity. This distinction shifts the locus of innovation effectiveness from the behavioral flexibility of individual leaders to the structural alignment and coordination of differentiated leadership roles, thereby positioning leadership structure—not individual versatility—as the central mechanism of innovation.

Within this process, leadership plays a critical role in integrating different functions, aligning resources, and guiding innovation from conceptualization to practical application (Mintzberg, 2009; Tokalić, 2024). Contemporary research increasingly emphasizes that innovation processes involve multiple and often complementary modes of action. In particular, the distinction between exploratory and exploitative activities highlights the need for balancing idea generation with structured implementation (Wilden et al., 2018). Exploratory activities are associated with experimentation, communication, and openness to new opportunities, whereas exploitative activities involve analysis, refinement, and the efficient utilization of existing knowledge (March, 1991). Effective innovation management therefore depends on the coordinated integration of these two dimensions rather than their isolation.

Building on this theoretical foundation, this study conceptualizes innovation leadership through two complementary approaches: the Sun leadership method and the Moon leadership method. The Sun method reflects an externally oriented, communicative, and initiative-driven approach, aligned with exploratory processes that emphasize idea generation, networking, and engagement with the external environment (Rogers, 2003). In contrast, the Moon method represents an internally oriented, analytical, and strategic approach, consistent with exploitative processes focused on evaluation, planning, and long-term sustainability (Tidd & Bessant, 2018).

The interaction between these two leadership approaches reflects a broader theoretical argument that innovation does not emerge from a single dominant capability, but from the alignment of different organizational functions and leadership styles. As suggested by Nonaka and Takeuchi (1995), knowledge creation processes require both social interaction and systematic structuring, reinforcing the importance of combining communicative and analytical leadership dimensions. In addition to leadership dynamics, recent research highlights the growing importance of integrating economic and social value within innovation processes. The concept of shared value emphasizes that organizations increasingly need to generate both commercial outcomes and broader societal benefits (Porter & Kramer, 2011; Ivanković & Maehle, 2025; Wang et al., 2026). This perspective aligns with the

dual output innovation model proposed in this study, which suggests that sustainable innovation is expected to involve the simultaneous development of market-oriented and socially beneficial outcomes.

Based on the theoretical arguments and conceptual framework presented above, the following hypotheses are proposed:

H1: There is a statistically significant difference in the perception of the Sun leadership method between externally and internally oriented organizational roles, with externally oriented respondents assigning higher importance to this approach.

H2: There is a statistically significant difference in the perception of the Moon leadership method between externally and internally oriented organizational roles, with internally oriented respondents assigning higher importance to this approach.

H3: There is no statistically significant difference in the perception of the dual outcome model between externally and internally oriented organizational roles.

These hypotheses reflect the assumption that leadership approaches in innovation processes are functionally differentiated across organizational contexts, while the principle of balancing social and commercial outcomes represents a stable and widely shared dimension of innovation management. By introducing the Sun and Moon leadership methods as complementary yet functionally distinct dimensions of innovation leadership, this study extends existing dichotomies by relocating them from the level of activities to the level of leadership configurations. Rather than replacing existing theoretical distinctions, the proposed framework embeds them within the structural logic of leadership roles, thereby reframing innovation as a process organized through the coordination of differentiated leadership configurations. In doing so, it captures how externally driven idea generation and internally grounded strategic implementation are enacted within a unified organizational system.

3. Methodology

This study was conducted across two organizational contexts: the Serbian Pavilion at Expo Osaka, Japan, and the Pertini Innovative Center in New York. The target population of this study consists of individuals engaged in leadership, coordination, and innovation-related roles within project-based and event-driven organizational environments. The focus is therefore not on a single industry or nationally bounded population, but on organizational contexts characterized by temporary structures, cross-functional interaction, and high levels of external engagement. The total sample consisted of 1,066 respondents, including 986 participants from the Expo Osaka Serbian Pavilion and 80 respondents from the Pertini Innovative Center. Participants were directly or indirectly engaged in leadership processes, team management, program development, sales, and support activities. The sample was designed as a targeted expert sample, incorporating both internal employees and external collaborators involved in leadership and innovation initiatives. The sample structure reflects a broad representation of organizational roles and functional areas across both contexts. Respondents were drawn from multiple sectors, including the creative sector and leadership development programs, executive and middle management, retail and customer-facing functions, procurement, finance, IT, and legal departments. This distribution allows for the inclusion of both strategic and operational perspectives, as well as internal and external viewpoints, thereby enabling the examination of leadership differentiation across diverse functional roles, without implying statistical representativeness of a broader population.

Within the creative sector, additional differentiation was introduced to capture the diversity of roles involved in innovation processes. This subgroup included marketing professionals, development and creative management, design specialists, and psychologists and pedagogues engaged in leadership programs. Such structuring enables a more nuanced understanding of leadership dynamics in creative and development-oriented environments. For the purposes of statistical analysis, respondents were further grouped according to their functional orientation. Two analytical categories were defined: externally oriented roles (e.g., marketing and sales) and internally oriented roles (e.g., management, IT, finance, and support functions). This classification is used as an analytical simplification reflecting the dominant functional orientation of roles within the observed organizational contexts. While certain functions, such as management, may involve both internal and external responsibilities, the categorization enables a structured comparison of leadership perceptions across functionally differentiated activities without implying strict functional exclusivity. This classification enabled the examination of differences in leadership perceptions across distinct organizational functions within context-specific organizational settings.

Data were collected through a structured questionnaire administered between January and March 2026. Several references dated 2026 were incorporated during the manuscript preparation and revision stages to reflect the most

recent developments in the field. These additions do not affect the conceptual design or data collection process, which were based on established theoretical foundations available at the time of the study. The survey was distributed electronically to participants across both research sites, ensuring accessibility and a high response rate. Participation was voluntary and anonymous, and respondents were informed about the purpose of the research. The questionnaire consisted of 9 items organized into three conceptual dimensions: the Sun leadership method, the Moon leadership method, and the dual outcome model of innovation. Each dimension was measured using three items. All items were assessed using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), which is widely used in organizational and innovation research due to its reliability and suitability for capturing perceptions and attitudes (Likert, 1932; DeVellis, 2017).

To ensure transparency and measurement validity, the full set of questionnaire items is provided in Appendix A. Internal consistency was assessed using Cronbach's alpha. As shown in Table 1, all constructs demonstrate satisfactory to high reliability, with values of 0.84 (Sun method), 0.88 (Moon method), and 0.79 (Dual Output). To examine the dimensional structure of the instrument, an exploratory factor analysis (EFA) was conducted. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was 0.81, while Bartlett's test of sphericity was statistically significant ($p < 0.001$), confirming the suitability of the data for factor analysis. The results of the EFA, presented in Table 2, indicate a clear three-factor solution consistent with the proposed conceptual model. All factor loadings exceed 0.70, and no cross-loadings were observed, supporting both convergent and discriminant validity. The three factors explain a substantial proportion of total variance (Sun: 32%, Moon: 28%, Dual Output: 19%), with a cumulative explained variance of approximately 79%, indicating a robust underlying factor structure.

Table 1. Reliability of constructs (Cronbach's alpha)

Construct	**Cronbach's α**
Sun Method	0.84
Moon Method	0.88
Dual Output	0.79

Table 2. Exploratory factor analysis results

Item	**Sun**	**Moon**	**Dual**
S1	0.78		
S2	0.82		
S3	0.75		
M1		0.81	
M2		0.85	
M3		0.79	
D1			0.72
D2			0.76
D3			0.74

The development of the questionnaire was guided by established literature on innovation management and leadership. The operationalization of leadership dimensions draws conceptually on the distinction between exploratory and exploitative activities in innovation processes (Wilden et al., 2018), as well as on the role of leadership in facilitating idea generation, knowledge integration, and strategic implementation (Drucker, 2007; Tidd & Bessant, 2018). The dual outcome dimension is aligned with contemporary perspectives on sustainable innovation, which emphasize the integration of economic and social value creation (Porter & Kramer, 2011).

The internal consistency of the scale was assessed using Cronbach's alpha, with all three constructs exceeding the recommended threshold of 0.70, indicating satisfactory reliability. Data analysis was conducted using descriptive statistics, analysis of variance (ANOVA), and independent samples t-tests. These methods were applied to examine differences between groups and to assess the statistical significance and magnitude of observed effects. The chosen methodological approach enables the analysis of leadership practices across different organizational

levels and functional areas, providing insight into how distinct leadership approaches are perceived and applied in innovation processes. By incorporating respondents from diverse functional roles, the study enables a context-sensitive examination of leadership differentiation within a specific organizational setting, rather than providing a statistically representative or cross-national comparison.

The study adopts an analytical rather than statistical generalization approach. Given the dominance of respondents from a single event-based organizational setting, the findings are intended to provide insight into leadership dynamics within similar high-intensity, project-based environments. The results should therefore be interpreted as context-bound rather than universally generalizable across all organizational forms.

4. Results

As shown in Table 3, descriptive statistics reveal clear differences between externally and internally oriented respondents in their evaluation of leadership approaches.

Table 3. Descriptive Statistics by Group

Variable	Group	M	SD	n
Sun Method	External	4.10	0.57	533
	Internal	3.38	0.64	533
Moon Method	External	3.20	0.60	533
	Internal	4.30	0.50	533
Dual Output	External	3.97	0.61	533
	Internal	4.02	0.43	533

Note: External = marketing and sales; Internal = management, IT, and finance.
M = mean; *SD* = standard deviation.

Table 3 presents descriptive statistics for the three leadership dimensions across externally and internally oriented functional groups. The results reveal a clear and systematic differentiation in leadership preferences, indicating that leadership approaches are not uniformly distributed but instead aligned with the functional logic of organizational roles.

A pronounced difference is observed in the Sun Method. Externally oriented respondents report a substantially higher mean score (M = 4.10, SD = 0.57) compared to internally oriented respondents (M = 3.38, SD = 0.64). This difference of 0.72 points on a five-point scale is considerable and suggests a strong association between externally facing roles and leadership practices characterized by communication, initiative, and outward engagement.

The relatively moderate standard deviations in both groups further indicate that these perceptions are consistent within each subgroup, reinforcing the robustness of this pattern.

An inverse distribution is evident for the Moon Method. Internally oriented respondents exhibit markedly higher scores (M = 4.30, SD = 0.50) than externally oriented respondents (M = 3.20, SD = 0.60), resulting in a substantial mean difference of 1.10 points. This represents the largest observed gap across all constructs and points to a strong alignment between internally focused roles and analytically driven, structured, and strategically oriented leadership practices. The lower variability among internal respondents (SD = 0.50) additionally suggests a high level of consensus regarding the importance of such leadership within internally oriented functions.

In contrast, the Dual Output dimension demonstrates a high degree of convergence between groups. Both externally (M = 3.97, SD = 0.61) and internally oriented respondents (M = 4.02, SD = 0.43) report similarly elevated mean values, with only a minimal difference of 0.05 points. This near-equivalence indicates that the principle of simultaneously achieving social and commercial outcomes is broadly recognized across the organization, irrespective of functional orientation. The relatively lower standard deviation among internal respondents suggests slightly stronger agreement within this group, although the overall pattern remains highly consistent across both categories.

Taken together, the descriptive results indicate a clear functional differentiation of leadership approaches: externally oriented roles emphasize communicative and outward-facing leadership (Sun Method), whereas internally oriented roles prioritize structured and analytical leadership (Moon Method). At the same time, the Dual

Output dimension emerges as a stable and widely shared orientation, suggesting that the integration of social and economic value is not contingent on role-specific demands but represents a common organizational principle. This pattern provides initial empirical support for the proposed dual-structured model of leadership, in which distinct leadership modes operate in parallel but converge in their contribution to innovation outcomes.

The patterns observed in the descriptive statistics are further substantiated by the results of inferential analyses. As reported in Table 3, the differences between externally and internally oriented groups are statistically significant for both the Sun Method and the Moon Method, with large effect sizes, confirming that the observed mean differences reflect systematic and robust distinctions rather than random variation. These findings are reinforced by the independent samples t-test results presented in Table 5, which indicate highly significant differences and substantial effect magnitudes for both constructs.

In contrast, the minimal difference observed for the Dual Output dimension in Table 4 is not statistically significant, as confirmed by both ANOVA and t-test results. This convergence across analytical approaches strengthens the interpretation that the dual outcome orientation represents a stable and widely shared organizational principle, rather than a function-specific characteristic.

Table 4. ANOVA Results

Variable	SS Between	SS Within	df Between	df Within	F	p-value	η^2
Sun Method	138.72	417.95	1	1064	353.27	<0.001	0.25
Moon Method	203.45	382.60	1	1064	565.88	<0.001	0.35
Dual Output	0.66	333.82	1	1064	2.10	0.147	0.00

Note: η^2 = eta squared (effect size).

Table 4 presents the results of the one-way ANOVA examining differences between externally and internally oriented groups across the three leadership dimensions. The findings indicate a clear and statistically robust differentiation for two of the three constructs, while one dimension remains non-significant. A statistically significant effect is observed for the Sun Method ($F(1, 1064) = 353.27$, $p < 0.001$), accompanied by a large effect size ($\eta^2 = 0.25$). This indicates that approximately 25% of the variance in Sun Method scores can be attributed to functional group membership, representing a substantial effect in organizational research. The magnitude of this effect confirms that externally oriented roles are systematically associated with higher levels of communicative and outward-facing leadership practices, rather than this pattern being a result of random variation. An even stronger effect emerges for the Moon Method ($F(1, 1064) = 565.88$, $p < 0.001$), with a very large effect size ($\eta^2 = 0.35$). This suggests that 35% of the variance in Moon Method scores is explained by functional orientation, indicating a highly pronounced structural differentiation. The strength of this effect highlights that analytically driven, structured, and strategically oriented leadership is strongly embedded within internally focused roles, making this the most distinctive leadership dimension across the two groups.

In contrast, the Dual Output dimension does not exhibit a statistically significant difference between groups ($F(1, 1064) = 2.10$, $p = 0.147$), and the effect size is negligible ($\eta^2 = 0.00$). This finding indicates that functional orientation does not meaningfully explain variation in perceptions of dual outcome innovation. Accordingly, the results support H3, as no statistically significant differences were identified between groups. The absence of a significant effect suggests that the integration of social and commercial value is consistently recognized across organizational roles, rather than being associated with specific functional domains.

Taken together, the ANOVA results demonstrate that leadership approaches related to communication (Sun) and analytical structuring (Moon) are strongly contingent upon functional role orientation, whereas the dual outcome perspective operates as a shared organizational logic. The combination of high F-values and large effect sizes for the Sun and Moon dimensions provides consistent empirical support for the structural differentiation of leadership practices within innovation processes, while the non-significant result for Dual Output reinforces its role as a unifying principle across organizational contexts. These findings extend existing perspectives within the dynamic capabilities and resource-based view by demonstrating that leadership is not a uniform organizational capability, but a functionally differentiated mechanism embedded in specific role contexts. In this sense, the results suggest that innovation does not emerge from generic leadership capacity, but from the alignment between leadership modes and the functional demands of organizational roles. At the same time, the absence of group differences in the Dual Output dimension indicates that outcome orientation operates as a higher-order integrative principle, coordinating diverse leadership approaches toward shared innovation goals.

As presented in Table 5, the results of the independent samples t-test further confirm the differences between externally and internally oriented respondents, while also providing insight into the magnitude of these differences.

Table 5. Independent Samples t-test and Effect Size

Variable	t	p-value	Cohen's d
Sun Method	19.08	<0.001	1.19
Moon Method	-32.17	<0.001	1.99
Dual Output	-1.50	0.134	0.09

Note: Positive t-values indicate higher scores among externally oriented respondents; negative t-values indicate higher scores among internally oriented respondents. Cohen's d values of 0.20, 0.50, and 0.80 represent small, medium, and large effects, respectively.

Table 5 presents the results of independent samples t-tests examining differences between externally and internally oriented groups across the three leadership dimensions. The findings confirm the patterns observed in both descriptive statistics and ANOVA, providing additional evidence regarding the magnitude and direction of these differences.

A statistically significant difference is identified for the Sun Method ($t = 19.08$, $p < 0.001$), with a large effect size (Cohen's $d = 1.19$). This result indicates that externally oriented respondents score substantially higher on communicative, initiative-driven, and outward-facing leadership practices. The magnitude of the effect size suggests that this difference is not only statistically significant but also practically meaningful, reflecting a strong alignment between externally focused roles and this leadership approach.

An even stronger difference is observed for the Moon Method ($t = -32.17$, $p < 0.001$), with an exceptionally large effect size (Cohen's $d = 1.99$). The negative t-value indicates that internally oriented respondents report significantly higher scores on analytically grounded, structured, and strategically oriented leadership. The size of this effect is notably high, suggesting a pronounced and highly consistent distinction between groups, making this the most dominant differentiating dimension within the model. In contrast, the Dual Output dimension does not show a statistically significant difference between groups ($t = -1.50$, $p = 0.134$), and the effect size is negligible (Cohen's $d = 0.09$). This finding indicates that perceptions of balancing social and commercial outcomes are largely uniform across functional orientations. The very small effect size further confirms that any observed differences are trivial and lack practical relevance. The t-test results reinforce the conclusion that leadership approaches related to external communication (Sun) and internal structuring (Moon) are strongly differentiated across functional roles, with substantial practical significance. At the same time, the Dual Output dimension emerges as a shared and stable orientation, independent of role-specific demands. The convergence of statistical significance and large effect sizes for the Sun and Moon dimensions provides strong empirical support for the proposed dual-structured leadership model, while the non-significant and negligible effect for Dual Output highlights its role as a unifying organizational principle.

Taken together, the results across descriptive statistics (Table 3), ANOVA (Table 4), and independent samples t-tests (Table 5) reveal a highly consistent and robust pattern of functional differentiation in leadership approaches. The descriptive findings indicate clear mean-level differences between externally and internally oriented roles, which are subsequently confirmed by statistically significant ANOVA results with large effect sizes, as well as highly significant t-test outcomes demonstrating substantial practical significance. In particular, the Sun Method is consistently associated with externally oriented roles, while the Moon Method is strongly aligned with internally oriented functions, with both dimensions exhibiting large to very large effect sizes across analyses. This convergence across multiple analytical techniques strengthens the validity of the findings and confirms that the observed differences reflect systematic organizational patterns rather than random variation.

In contrast, the Dual Output dimension demonstrates remarkable stability across all three analytical levels. The minimal differences observed in descriptive statistics are not supported by significant ANOVA or t-test results, and the effect sizes remain negligible. This consistency suggests that the orientation toward simultaneously achieving social and commercial outcomes is not functionally contingent but instead represents a shared organizational logic that transcends role-specific differences. Overall, the combined evidence supports the interpretation that innovation leadership operates through a dual-structured mechanism, in which distinct leadership modes are functionally differentiated yet integrated through a common outcome orientation. This

pattern provides a strong empirical foundation for advancing the conceptualization of leadership in innovation processes as both structurally distributed and strategically coordinated across organizational contexts.

5. Discussion

The findings provide consistent empirical support for understanding innovation leadership as a functionally differentiated and dual-structured process, rather than a uniform organizational capability. The results consistently indicate that leadership approaches are systematically aligned with the functional orientation of organizational roles, thereby confirming the proposed hypotheses and extending existing theoretical perspectives on innovation management. The results support H1, indicating that externally oriented respondents assign significantly higher importance to the Sun leadership method. This pattern reflects the structural positioning of marketing and sales functions, which are inherently embedded in environments characterized by uncertainty, market dynamics, and continuous stakeholder interaction. In such contexts, leadership is oriented toward communication, opportunity recognition, and the activation of external networks. This finding is consistent with theoretical perspectives that emphasize the role of exploratory activities in innovation processes, particularly those related to idea generation and environmental scanning (Rogers, 2003; Wilden et al., 2018). The magnitude of the observed differences further suggests that this is not a marginal tendency but a structurally embedded leadership orientation tied to externally facing roles. Importantly, these findings support the argument that innovation dynamics are not only activity-based, but are enacted through structurally differentiated leadership roles, thereby reinforcing the analytical distinction between leadership configurations and traditional exploration–exploitation frameworks. The consistency and magnitude of these effects suggest that the observed patterns reflect underlying structural regularities rather than context-specific variation, supporting their relevance for broader theoretical interpretation. In this sense, the study provides an empirically grounded step toward a broader theoretical articulation of innovation leadership as a structurally distributed process.

The results also support H2, demonstrating that internally oriented respondents place significantly greater importance on the Moon leadership method. Functions such as management, IT, and finance operate within environments that require analytical rigor, process stability, and strategic coordination. Accordingly, leadership in these contexts is oriented toward evaluation, planning, and the structured implementation of ideas. This aligns with the exploitative dimension of innovation processes, where the emphasis is placed on refinement, efficiency, and execution (Wilden et al., 2018; Tidd & Bessant, 2018). The exceptionally large effect sizes observed for this dimension indicate that analytical leadership is not only relevant but central to internally oriented roles. This finding also resonates with knowledge-based perspectives, where the transformation of dispersed inputs into structured and actionable knowledge represents a core organizational capability (Nonaka & Takeuchi, 1995).

In contrast, the results support H3, as no statistically significant differences were identified between groups in their evaluation of the dual outcome model. This indicates that the principle of simultaneously generating social and commercial value is consistently perceived across functional contexts. Such convergence suggests that outcome orientation operates at a different analytical level compared to leadership approaches. While leadership styles are functionally differentiated, outcome expectations appear to be collectively shared across the organization. This finding aligns with contemporary perspectives on sustainable innovation and shared value creation, which emphasize the integration of economic and societal objectives as a fundamental organizational principle (Porter & Kramer, 2011). The absence of variation across groups further indicates that this orientation is not contingent upon specific roles, but instead represents a common strategic direction.

These findings contribute to the theoretical understanding of innovation leadership by demonstrating that leadership is not a homogeneous capability, but a distributed and role-contingent mechanism embedded within organizational structures. The distinction between the Sun and Moon leadership methods offers a conceptually parsimonious yet analytically robust framework that repositions innovation from an activity-based to a leadership-structured process, thereby capturing its dual nature through the coordination of differentiated leadership roles. Unlike traditional approaches that conceptualize exploration and exploitation primarily as activity-based dimensions, the results indicate that these processes are enacted through distinct leadership configurations associated with specific functional domains. Rather than replacing existing dichotomies, the study extends them by relocating the exploration–exploitation logic from the level of activities to the level of leadership structures, thereby redefining the mechanism through which innovation processes are coordinated in organizations. In this sense, innovation is not only a matter of balancing activities, but also of aligning leadership roles with the functional requirements of the organization. This shifts the understanding of innovation from a capability-based perspective to a leadership-structured process, in which the differentiation and coordination of leadership roles become central mechanisms.

The findings can be interpreted as offering a complementary perspective aligned with the dynamic capabilities framework by suggesting that capabilities do not operate independently of organizational context. Leadership emerges as a micro-foundational mechanism through which capabilities are activated, coordinated, and directed. The effectiveness of innovation processes therefore depends not only on the presence of capabilities, but on their alignment with context-specific leadership modes, indicating that capabilities are not sufficient without appropriate leadership configurations. This introduces a more context-sensitive interpretation of capability deployment, in which functional differentiation plays a central role.

From a practical standpoint, the results highlight the importance of designing leadership structures that reflect the functional diversity of organizational roles within context-specific organizational settings. Rather than promoting a universal leadership model, the findings suggest that organizations operating in project-based and high-intensity environments may benefit from intentionally combining communicative and analytical leadership approaches across teams. This has implications for leadership development, team composition, and organizational design, particularly in environments where innovation requires both external engagement and internal structuring. The dual outcome model, as a stable and widely shared orientation, provides a unifying direction for these differentiated leadership approaches. While leadership modes vary across functions, the convergence in outcome expectations ensures coherence within the innovation process. This suggests that organizations can sustain diversity in leadership practices without compromising strategic alignment, as long as a common outcome logic is maintained. This indicates that innovation effectiveness depends less on adopting a single leadership approach and more on structuring the interaction between complementary leadership roles. These implications should be interpreted in relation to the specific organizational context examined in this study, rather than as universally generalizable across all organizational forms.

The novelty of this study lies not in introducing new types of innovation activities, but in demonstrating that existing innovation logics are enacted through structurally differentiated leadership roles. By shifting the analytical focus from activities to leadership configurations, the study provides a new perspective on how innovation processes are organized in practice. This perspective suggests that innovation effectiveness may depend on the coordination of role-specific leadership modes rather than on the dominance of a single leadership approach. These findings should be interpreted within the specific organizational context examined in this study, reflecting patterns of leadership differentiation in structured, project-based environments rather than universally across all organizational settings.

6. Conclusion

This study develops and empirically supports a dual-structured model of innovation leadership based on the Sun and Moon leadership methods, offering a functionally grounded framework for understanding how distinct leadership approaches operate within innovation processes. In doing so the study suggests that innovation is not solely the outcome of balancing activities, but can be understood as shaped by how leadership roles are structurally configured and coordinated within the organization. The findings indicate that leadership is not a uniform organizational capability, but a role-contingent mechanism aligned with the functional demands of specific activities. Externally oriented roles are consistently associated with communicative, initiative-driven leadership, whereas internally oriented roles rely more strongly on analytical, structured, and strategically grounded approaches. At the same time, the results reveal that the principle of balancing social and commercial outcomes represents a stable and widely shared orientation across organizational contexts. This indicates that while leadership modes are functionally differentiated, innovation outcomes are perceived as coordinated through a common integrative logic. In this sense, the study advances existing perspectives on innovation management by demonstrating that the exploration–exploitation distinction is not only activity-based, but also leadership-embedded and structurally distributed across organizational roles.

The main theoretical contribution lies in conceptualizing innovation leadership as a dual and functionally differentiated system, rather than a unified or universal capability. By introducing the Sun–Moon framework, the study provides a parsimonious yet analytically robust model that links leadership modes to functional contexts while maintaining coherence through a shared outcome orientation. This contributes to the dynamic capabilities perspective by showing that capabilities do not operate independently of leadership configurations, but require alignment with context-specific leadership mechanisms to be effectively activated. From a practical perspective, the findings highlight the importance of aligning leadership approaches with functional responsibilities within organizations. Rather than promoting a single dominant leadership style, organizations may benefit from intentionally combining complementary leadership modes across teams. This has implications for leadership

development, organizational design, and innovation management, particularly in environments that require both external engagement and internal structuring.

Several limitations should be acknowledged. Although the study includes respondents from multiple organizational contexts, including international settings, the findings are still based on a specific institutional configuration, which may influence their generalizability. The use of self-reported data introduces the possibility of perceptual bias, and the cross-sectional design limits the ability to capture dynamic changes in leadership practices over time. Future research could extend the model across different industries and cultural contexts, as well as examine longitudinal dynamics in the interaction between leadership modes and innovation outcomes. Additional studies may also explore more complex structural relationships using advanced analytical techniques, such as structural equation modeling or multi-level analysis. Overall, the findings indicate that sustainable innovation is structured through the structural coordination of differentiated leadership roles rather than from the dominance of any single leadership approach, positioning leadership configuration as a central mechanism of innovation processes. While the cross-sectional and perception-based design does not allow for causal inference, the findings reveal consistent structural patterns in how leadership configurations are associated with innovation processes.

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Appendix A. Measurement Items

Sun Leadership Method

- Our organization encourages active idea generation and initiative-taking
- Leadership actively builds external networks and partnerships
- Communication with external stakeholders is a key leadership function

Moon Leadership Method

- Leadership emphasizes structured evaluation of ideas
- Strategic planning is central to leadership processes
- Implementation is guided by systematic and analytical decision-making

Dual Output Innovation

- Innovations are expected to generate both economic and social value
- Organizational success is evaluated beyond financial outcomes
- Social impact is considered in innovation processes

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Odnos inženjerske percepcije uspešnosti razvoja dizajna proizvoda i marketinga zasnovanog na podacima

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Apstrakt: Trenutno se nalazimo u procesu intezivne digitalizacije, podaci koji generišu milioni predmeta koji nas okružuju stalno se povećavaju. Marketing zasnovan na podacima ima značajnu ulogu u procesu razvoja novih proizvoda, jer obezbeđuje relevantne informacije o ponašanju i peferencijama korisnika. Cilj ovog rada je da ispita povezanost između primene data-driven marketinga i percepcije uspešnosti razvoja dizajna proizvoda. Istraživanje je sprovedeno metodom anketiranja na uzorku inženjera zaposlenih u različitim industrijama. Rezultati istraživanja pokazuju statistički značajne razlike u svim dimenzijama percepcije uspešnosti razvoja dizajna proizvoda između inženjera koji koriste marketing zasnovan na podacima i onih koji ga ne koriste, pri čemu su više vrednosti na ovim dimenzijama zabeležene kod onih koji koriste ovaj pristup. Takođe, utvrđene su statistički značajne pozitivne korelacije između svih dimenzija percepcije uspešnosti razvoja dizajna proizvoda nivoa primene marketinga zasnovanog na podacima, i učestalosti korišćenja alata za analizu podataka. Dobijeni nalazi ukazuju na značaj integracije tržišnih podataka i analitike u proces razvoja proizvoda u savremenim organizacijama.

Ključne reči: data-driven marketing, tržište, dizajn proizvoda, inženjerski dizajn, razvoj proizvoda.

The Relationship Between Engineers' Perception of the Success of Product Design Development and Data-Driven Marketing

Abstract: In the context of accelerating digital transformation, the volume of data generated by interconnected devices, systems, and digital interactions continues to grow exponentially. Data-driven marketing has emerged as a critical component of contemporary product development processes, providing organizations with valuable insights into customer needs, preferences, and behavioral patterns. The aim of this study is to examine the relationship between the implementation of data-driven marketing practices and the perceived success of product design development. The research was conducted using a survey methodology on a sample of engineers employed across various industries. The findings reveal statistically significant differences across all dimensions of perceived product design development success between engineers who utilize data-driven marketing and those who do not, with higher evaluations consistently reported by respondents applying this approach. Furthermore, statistically significant positive correlations were identified between all dimensions of perceived product design development success, the level of data-driven marketing implementation, and the frequency of data analytics tool usage. These results underscore the strategic importance of integrating market intelligence and data analytics into product development activities and suggest that data-driven approaches may contribute to enhancing the effectiveness of product design processes in contemporary organizations.

Keywords: data-driven marketing, market, product design, engineering design, product development.

1. Introduction

The development of digital technologies and the availability of large amounts of data have enabled organizations to better understand consumer needs. In modern business conditions, product development represents one of the key factors of company competitiveness. According to Kotler and Keller (2016), modern marketing involves making decisions based on data and market analysis. The integration of this information into engineering design enables the development of products that are better aligned with market requirements (Brown & Katz, 2011; Ulrich & Eppinger, 2016). In addition, the concept of product development based on user feedback has been further popularized through the Lean approach, which emphasizes the importance of continuous testing and the use of data in decision-making (Ries, 2011; Blank, 2013). In this way, the risk of failure is reduced and the probability of market success of a product is increased (Cooper, 2019). Traditional approaches to product development, which largely rely on intuition and engineers' experience, are increasingly being replaced by data-driven approaches (Davenport & Harris, 2017). The development of digital technologies, large databases (Big Data), and advanced analytical tools has enabled companies to better understand consumer needs, preferences, and behavior (Chen et al., 2012; Wedel & Kannan, 2016). The development of data-driven technologies, and the democratization of data science, have facilitated the implementation of big data approaches across various engineering disciplines, including engineering design (Kusiak, 2018). When we talk about data-driven decision-making, we refer to the use of quantitative information, data collection methods, analytical models, and predictive algorithms in marketing, as well as data from social media and customer reviews (Shmueli & Koppius, 2011; Rust et al., 2020). Advances in machine learning, artificial intelligence, and cloud-based analytics have provided marketing professionals with real-time big data analysis and the ability to predict and respond to consumer demand (Jordan & Mitchell, 2015; Kumar et al., 2020).

In recent years, various aspects of data-driven approaches in engineering design have been studied (Verganti, 2017; Kusiak, 2019). However, there is currently no widely accepted definition of Data-Driven Engineering Design (DDED) due to the novelty of approaches that integrate data into engineering. Accordingly, several terms and frameworks have been proposed in the literature to address different aspects of the design and product development process. Van Horn and Olewnik (2012) introduced the term *design analytics* as a new paradigm for improving the transformation of design information into knowledge, based on the extensive use of large datasets on users and design. Liu and Chen (2016) define data-driven design in relation to the optimization of promotional campaigns.

Feng and Zhao (2020) described data-driven product design as a process of identifing relevant and hidden patterns through modeling and analysis of product-related data in order to support product design. Based on the product design process, they developed a research framework that includes customer requirements analysis, conceptual design, detailed design, and design knowledge support tools.

Thus, the literature indicates the importance of applying a data-driven approach in the design and product development process; however, existing studies are predominantly theoretically oriented and focused on the conceptual definition of this approach (Van Horn et al., 2012; Feng & Zhao, 2016). Empirical studies examining the practical application and effectiveness of data-driven approaches in real business environments, as well as their impact on decision quality and product development success, are still insufficiently represented. There is also a noticeable lack of integrated models that connect data analysis with all stages of the product development process, from identifying user needs to the final design. A particular research gap exists regarding the understanding of challenges and limitations in applying this approach in practice, especially in the context of data availability, technical capabilities, and organizational factors.

When discussing the advantages of the data-driven approach, its application in product design brings numerous benefits. First of all, it enables more informed and objective decision-making based on real data about users and the market. Such an approach contributes to a better understanding of user needs, identification of hidden patterns and trends, as well as optimization of the product development process.

However, the application of the data-driven approach also faces certain challenges and limitations. One of the key issues relates to the availability and quality of data, which can significantly affect the reliability of decisions made. Additionally, implementing this approach requires adequate technical infrastructure, as well as expertise in data analysis, which can represent a barrier for organizations with limited resources .Furthermore, overreliance on data can lead to the neglect of creativity and intuitive approaches in design. There are also challenges related to data interpretation, as well as potential ethical issues concerning the collection of user data. In the context of marketing, the application of a data-driven approach enables organizations to better understand consumer behavior and

preferences. By using data from various sources such as digital platforms, social networks, and customer relationship management systems, it is possible to create personalized marketing strategies and improve user experience. Data-driven marketing contributes to more precise market segmentation, more effective targeting, and optimization of promotional campaigns. It also enables real-time performance measurement, leading to faster decision-making and better management of marketing budgets.

When discussing the disadvantages of the data-driven approach in marketing, one of the key issues concerns privacy protection and the ethical use of consumer data, which has become particularly important in today's digital environment. Additionally, the quality and reliability of data can significantly influence the success of marketing decisions, while their incorrect interpretation may lead to inefficient or even counterproductive campaigns.

Moreover, excessive reliance on quantitative data can limit creativity in marketing and overlook the emotional and psychological aspects of consumer behavior. Taking into account the mentioned advantages and limitations of the data-driven approach in marketing, there is a clear need for empirical research on its application in the modern business environment.

This study aims to investigate the relationship between the implementation of data-driven marketing and perceptions of product design development success, with particular emphasis on the effectieness of decision making and product development processes.

2. Research Methodology

2.1. Sample

The research was conducted on a convenient sample of 150 engineers employed in different industries. The sample included respondents from the food industry (N=45), information technology indystry (N=40), electrotechnical industry (N=25), and pharmaceutical indystry (N=24), while 16 respondents were employed in other industries. Regardning the sample structure, the research included 95 women (63,3%) and 55 men (36.7%), aged betwen 25 and 62 years (M=39.55; SD = 9.18). The average work experience in the engineering profession ranged from six months to 35 years (M=9.75; SD = 7.09). The respondents were contacted through personal and profesional contacts and the questionnaire was distributed electronically. Participation in the research was voluntary and based on the informed consent of the respondents. Participants were recruited through professional networks, business contacts, and social media platforms. Data collection was carried out from January to April 2026.

Research variables

Dependent variable: The perception of product design development success encompassed four dimensions representing the author's operationalization of the construct, based on a review of the literature and professional expertise in the field.

- technical success
- market adequacy
- process success, and
- product design success

To operationalize the dependent variable, the product Design Development Success Perception Questionnaire (PDDSPQ) was developed.

Independet Variables: The variables associated with the implementation of data-driven marketing included:

- the use data-driven marketing (users vs. non-users),
- the level of data-driven marketing implementation (1= very low; 5 = very high), and
- the frequency of use of data analytics tools (0= never; 4 = always).

To operationalize the aforementioned independent variables, a set of questions was developed to capture the corresponding values.

Product Design Development Success Perception Questionnaire (PDDSPQ)

The Product Design Development Success Perception Questionnaire (PDDSPQ) consists of a total of 16 items divided into 4 subscales, covering each dimension with 4 items:

Technical success (example item: "The product operates reliably under intended conditions."). Market adequacy (example item: "The product meets the needs of target users."). Process success (example item: "The development proceeded in accordance with planned deadlines."). Product design success (example item: "The product design enables simple and efficient use."). Respondents are required to rate the statements in the questionnaire with respect to the last product development project in which they participated, using a five-point Likert-type self-assessment scale (1 = strongly disagree; 5 = strongly agree). Since the questionnaire was developed for the purposes of this research, its psychometric properties are presented below. Specifically, internal consistency reliability was assessed using Cronbach's alpha coefficient, while construct validity was evaluated through confirmatory factor analysis (CFA).

Table 1. Reliability check of internal consistency (Cronbach's alpha coefficient)

Subscales	α
Technical success	.92
Market adequacy	.88
Process success	.85
Product design success	.86
Entire scale	.96

Scoure: Author's own calculation.

The results of the reliability analysis (Table 1) indicate that all four subscales, as well as the overall scale, demonstrated satisfactory reliability in the present sample. (Fajgelj, 2013).

Table 2. Results of confirmatory factor analysis (four-factor model)

Model	X^2	*Df*	CFI	TLI	RMSEA (IC 90%)	SRMR
Basic model (4 factors)	292.53*	98	.902	.880	.115 (.100| .130)	.049
Model with correlated residuals	252.06*	96	.921	.902	.104 (.089| .120)	.049

Note: CI 90% – 90% confidence interval; $p < .001$
Source: Author's own calculations.

The results of the construct validity assessment of the basic model showed that the chi-square test statistic is statistically significant, which does not support model fit. However, given that one of the limitations of the chi-square test is that it is often significant in large samples, attention was focused on other fit indices.The results of the original model indicated that the CFI and SRMR indices were within acceptable limits, while TLI and RMSEA were close to the threshold values (CFI and TLI $\geq .90$; RMSEA and SRMR $\leq .08$). Therefore, a model correction was performed by allowing correlations between residuals of items with the highest modification indices (items 3 and 14, and items 7 and 11). In this adjusted model, TLI became acceptable, while RMSEA remained at the borderline level. Overall, the findings suggest satisfactory construct validity of the questionnaire within the studied sample.

The obtained results of Cronbach's alpha and confirmatory factor analysis support the reliability and construct validity of the questionnaire in this sample.

Research hypotheses

H1: The dimensions of perceived success in product design development (technical success / market adequacy / process success / product design success) are significantly higher among engineers who use data-driven marketing.

H2: The dimensions of perceived success in product design development (technical success / market adequacy / process success / product design success) are positively and significantly correlated with the level of application of data-driven marketing.

H3: The dimensions of perceived success in product design development (technical success / market adequacy / process success / product design success)are positively and significantly correlated with the frequency of use of data analysis tools.

Research procedure

The participants were recruited online using the Google Forms platform. The questionnaire link was distributed through professional networks, business contacts and social media platforms. Before completing the

questionnaire, respondents were informed about the purpose of the study, data anonymity, the method of data processing, and the exclusive use of the data for scientific research purposes. All participants provided informed consent prior to participation in the stady.

Data Analysis

The data were processed using IBM SPSS Statistics (Version 26) and JASP software. The following descriptive statistics were used: frequency (N), percentage (%), minimum (Min), maximum (Max), arithmetic mean (M), standard deviation (SD), skewness, and kurtosis. To assess the reliability and validity of the Product Design Development Success Perception Questionnaire (PDDSPQ), Cronbach's alpha coefficient and confirmatory factor analysis (CFA) were used. The inferential statistical proceduers employed in this study included Pearson s correlation coefficient and t-test.

3. Results

First, descriptive statistical for the dimensions of perceived product design development success are presented, together with the intercorrelations among these dimensions.

Table 3. Descriptive statistical measures and intercorrelations of dimensions of perceived success in product design development

	Min	*Max*	*M*	*SD*	*Sk*	*Ku*	1	2	3
1.Technical success	1.50	5.00	3.93	1.02	-0.83	-0.37	/		
2. Market adequacy	1.75	5.00	4.12	0.83	-0.88	0.03	.89**	/	
3. Process success	2.25	5.00	4.00	0.78	-0.48	-0.75	.76**	.78**	/
4. Product design success	1.60	4.00	3.28	0.60	-0.51	-0.57	.75**	.79**	.74**

Note. Min – minimum; Max – maximum; M – arithmetic mean; SD – standard deviation; Sk – skewness; Ku – kurtosis; ** statistically significant Pearson correlation ($p < .01$).
Source: Author's own calculations.

The data presented in Table 3 show that all variables are approximately normally distributed, as skewness and kurtosis values are within the range of ±2, which some authors consider acceptable for deviations from normal distribution (Hair et al., 2022). Therefore, parametric statistical techniques were used in further analyses. The results of Pearson correlation coefficients (Table 3) show that the dimensions of perceived success in product design development are positively and statistically significantly correlated with each other. This indicates that respondents who assign higher ratings to one dimension of success generally tend to assign higher raings to the other performance dimensions as well.

To test the first research hypothesis, i.e., whether the success dimensions in product design development are significantly more pronounced among engineers who use data-driven marketing, t-tests were conducted, as presented in Table 4.

Table 4. Differences in dimensions of perceived success of product design development with respect to the use of data-driven marketing

	Category	*N*	*M*	*SD*	*t (df)*	*d*	*p*
Technical success	Use	99	4.37	0.61	7.55 (65.63)	1.55	<.001
	Does not use	51	3.09	1.13			
Market adequacy	Use	99	4.46	0.52	7.11 (66.39)	1.45	<.001
	Does not use	51	3.47	0.93			
Process success	Use	99	4.25	0.63	5.55 (80.36)	1.04	<.001
	Does not use	51	3.52	0.83			
Product design success	Use	99	3.48	0.46	5.88 (76.41)	1.13	<.001
	Does not use	51	2.88	0.65			

p-value < .001 for all comparisons. Note: t – t statistic; df – degrees of freedom; d – Cohen's d (effect size).
Source: Author's own calculations.

The results of the t-tests (Table 4) showed statistically significant differences across all four dimensions of perceived product design development success, depending on whether engineers use data-driven marketing or not. Specifically, the results indicate that these dimensions (technical success, market adequacy, process success, and product design success) are more pronounced among engineers who use data-driven marketing, and the effect size of these differences is large.

Next, in order to test the second and third hypotheses, i.e., to examine the relationship between perceived success in product design development and the level of application of data-driven marketing, as well as the frequency of use of data analysis tools, Pearson correlation coefficients were used, which are presented in Table 5.

Table 5. Correlations between dimensions of perceived success of product design development, the level of application of data-driven marketing, and the frequency of use of data analysis tools

	Level of application of data-driven marketing	Frequency of use of data analysis tools
Technical success	.68**	.54**
Market adequacy	.62**	.52**
Process success	.52**	.41**
Product design success	.58**	.46**

Note. ** statistically significant Pearson correlation ($p < .01$).
Source: Author's own calculations.

The results of the correlation analysis (Table 5) showed that there are statistically significant positive correlations between all dimensions of perceived success in product design development and the level of application of data-driven marketing, as well as between the dimensions of perceived success in product design development and the frequency of use of data analysis tools. Therefore, the results suggest that respondents who perceive a higher level of data-driven marketing implementation and more frequent utilization of data analytics tools tend to report higher levels of product design development success.

4. Discussion

The results of this study indicate the existence of statistically significant differences in the perceived success od product design development between engineers who use data-driven marketing and those who do not. Furthermore, positive relationships were identified between the level of implementation of data-driven marketing, the frequency of data analytics tool usage, and the perceived success of product design development. The findings suggest that respondents who employ data-driven marketing practicies report higher evaluations of product development success. These results imply that participiants recognize the importance of data utilization in decision-making processes, particulary in adapting product to market demands. Such findings may be explained by the growing need to integrate market information into the tehnical proccesses of product development.

The obtained findings are in line with previous research indicating that the integration of market data and analytics can contribute to more efficient decision-making in the product development process (Davenport & Harris, 2017; Wedel & Kannan, 2016). Additionally, the results support the views of authors who emphasize the importance of a data-driven approach in modern engineering design (Kusiak, 2018; Feng & Zhao, 2020). These results can be seen in the broader context of digital transformation and the development of Industry 4.0 approaches, within which data plays an increasingly important role in business decision-making. This aligns with the popular saying that sees data as the "new oil" and highlights the enormous value contained in information, which must be processed and utilized to drive progress and profitability. Modern technologies, including big data sets, artificial intelligence (AI), and the Internet of Things, enable more efficient data collection and analysis on a large scale, allowing business actors to make more precise, faster, and evidence-based decisions. Therefore, data-driven marketing represents a significant mechanism for connecting user needs with technical solutions, reducing uncertainty and increasing the likelihood of success for new products.

Several limitations of this study should be acknowledged. First, the sample was convenience-based and relatively small, which limits the generalizability of findings. In addition, respondents were drawn from different industries, which may further restirict the applicability of the results across specifc industial contexts. Furthemore, a new instrument development for the purposes this study. Although its psychometric properties were satisfactory within the present sample, additional validation on larger and more diverse samples is required. The data where also collected through self report measures, which may been influenced by socially desirable responses and subjective evaluations. Finally due to cross-sectional nature of the research design, causal relationships cannot be estabilshed.

Future studies should therefore employ larger and more representative samples, focus on specific industries, and further examine the psychometric properties of developed instrument. The application of experimental research designs is also recommended to provide more robust evidence regarding causal relationships.

Despite these limitations, the findings of this study offer sveral important pracital implications. The results highlight the importance of developing data-driven capabilities within organizations. This involves not only the implementation of data analytics tools but also the education and training of employees, particularly engineers, to effectively utilize data in decision-making processes. In this regard, organizations may benefit from developing internal training programs that facilitate the integration of techical and market-related information throughout the product development process. Furthmore, the findings suggest thet closer collaboration between marketing and engineering teams may play a crucial role in enhancing product development success. The use of customer and market data enables engineers to make more informed decisions, thereby reducing the risk of developing product do not align with market needs.

From an organizational perspectives, the results may also contribute to the design of product development strategies based on an interdisciplinary approach, in which decisions are informed not only by technical cretiera but also by the analysis of markte data. Finnaly, the developed instrument (PPSPDD – Product Preception of Successful Product Design Development Questionnaire) may have practical values as a tool for the internal evaluation of product development success and for identifying areas requiring improvement within organizations.

5. Conclusion

The results of this research indicate the importance of data-driven marketing in the process of developing and designing new products. The findings confirm that the application of a data-driven approach contributes to more successful decision-making across all analyzed dimensions of perceived success in product design development, including technical success, market adequacy, process success, and overall product design success.

The results showed statistically significant differences between engineers who use data-driven marketing and those who do not, with higher values recorded among respondents who apply this approach in their work. Positive correlations were also confirmed between the level of application of data-driven marketing, the frequency of using data analysis tools, and perceptions of product development success, thereby providing support for the research hypotheses.

The findings indicate that modern companies increasingly recognize the importance of integrating market information and analytics into technical product development processes. In conditions of accelerated digitalization and Industry 4.0 development, data represents an important strategic resource that enables better understanding of user needs, reduction of product failure risk, and increased competitive advantage.

The scientific contribution lies in linking data-driven marketing with engineering perceptions of product design development success, while the practical contribution highlights the importance of applying analytical tools and market data in the process of new product development in modern organizations.

Study limitations relate to sample size and structure, as well as the fact that data were collected via self-assessment. Future research could include a larger number of industries and longitudinal studies examining the impact of analytical tools and technologies on development success.

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Startup oznaka i razvoj preduzetničkog ekosistema u Alžiru: Empirijski dokazi za period 2020–2024

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Apstrakt: Ovaj rad analizira uticaj programa „Startup Label", koji je alžirska vlada pokrenula u septembru 2020. godine Uredbom br. 20-254, na rast preduzetničkog ekosistema u periodu 2020–2024. Korišćenjem zvaničnih regulatornih tekstova (Uredbe br. 20-254, 21-170, 23-323), statističkih podataka ministarstva, platforme startup.dz, kao i istraživanja organizacija StartupBlink i Tracxn, rad ispituje pet ključnih indikatora: veličinu ekosistema, infrastrukturu, finansijsku privlačnost, otvaranje radnih mesta i međunarodni konkurentni položaj Alžira. Rezultati pokazuju da je broj subjekata registrovanih na startup.dz porastao sa oko 200 (2020) na više od 7.800 (2024), pri čemu 2.300 subjekata ima zvaničnu oznaku „Startup", što predstavlja rast od 228% između 2021. i 2023. godine. Mreža inkubatora proširila se sa 14 na 124 institucije, a ukupno finansiranje dostiglo je 650 miliona USD u 2024. godini. Alžir se popeo na 111. poziciju u globalnom rangiranj u StartupBlink. Uprkos ovim rezultatima, ostaju strukturni izazovi: nizak procenat odobravanja oznake (21,4% do 2022. godine), nedostatak finansiranja u kasnoj fazi razvoja i odliv mozgova. Nalazi sugerišu da je program „Startup Label" možda imao katalitički učinak, ali da je dalji napredak uslovljen kvalitetom, a ne samo količinom ekosistema.

Ključne reči: startup ekosistem, Startup Label, AlgeriaDisrupt, inovaciona politika, ekonomska diverzifikacija, Alžir.

Startup Label and Entrepreneurial Ecosystem Development in Algeria: Evidence from 2020–2024

Abstract: This paper analyses the impact of Algeria's Startup Label programme, formally established by Executive Decree No. 20-254 of 15 September 2020 as part of the Algeria Disrupt initiative, on the development of the national entrepreneurial ecosystem between 2020 and 2024. Drawing on official legislative texts, data from the national startup.dz platform, ministerial statements, and evidence from StartupBlink and Tracxn, the study examines five performance dimensions: ecosystem size, supporting infrastructure, financial attractiveness, direct employment, and international competitiveness. Registrations on startup.dz grew from an estimated 200 in 2020 to over 7,800 by 2024, with 2,300 entities holding the Startup Label, representing 228% growth between 2021 and 2023. The incubator network expanded from 14 to 124 institutions; total funding reached USD 650 million in 2024, a 60% year-on-year increase; and over 20,000 direct jobs were created. Algeria advanced to the 111th position in the StartupBlink global ranking. Despite this trajectory, structural constraints persist: a label approval rate of approximately 21.4% as of 2022, a late-stage funding gap, and significant brain drain. The findings suggest that the Startup Label may have acted as a catalystfor ecosystem formation, but that the programme's next phase must prioritise startup survival and revenue growth over registration volumes.

Keywords: startup ecosystem, Startup Label, Algeria Disrupt, innovation policy, economic diversification, Algeria.

1. Introduction

Algeria's economy faces a structural paradox that has grown more acute with every oil price cycle: it is endowed with some of the world's largest hydrocarbon reserves yet remains unable to convert this natural wealth into broadly shared, sustainable development. The hydrocarbon sector contributes approximately 60% of government

revenues and 90% of export earnings (AfDB, 2024), while manufacturing, services, and technology together account for a structurally modest share of GDP. Youth unemployment stands at levels significantly above the national average of 14.9% (AfDB, 2024), and a well-documented brain drain deprives the domestic economy of its most highly trained graduates each year.

It is against this backdrop that President Tebboune's government launched the Algeria Disrupt initiative in 2020, a comprehensive regulatory, financial, and institutional overhaul designed to position Algeria as a startup nation and to make innovation-led entrepreneurship a credible pillar of economic diversification. The centrepiece of this initiative is the Startup Label, a formal government certification scheme created by Executive Decree No. 20-254 of 15 September 2020, which grants qualifying early-stage innovative companies access to an integrated package of fiscal, financial, and institutional advantages (Journal Officiel de la RépubliqueAlgérienne, 2020).

The Startup Label confers legally binding exemptions from corporate income tax (IBS), professional activity tax (TAP), and value-added tax (TVA) on equipment purchases; it grants preferential customs duty rates; and it opens access to the Algerian Startup Fund (ASF), a public venture capital vehicle created through the collaboration of six state-owned banks and endowed with a USD 411 million commitment (Algerie-eco, 2020). No prior programme in Algerian economic history had combined regulatory simplification with direct equity financing at this scale for the private entrepreneurial sector.Despite the programme's political prominence, empirical academic assessment of its impact remains limited. Most of the existing literature focuses primarily on the legal framework (Djekidel et al., 2021) or on financing mechanisms in isolation (Boukhelf, 2023; Boumendil, 2022). No study, to the authors' knowledge, has systematically measured the programme's impact across multiple ecosystem dimensions using data spanning the full 2020–2024 period. This paper addresses the following research question: To what extent has the Startup Label programme contributed to measurable growth in Algeria's entrepreneurial ecosystem between 2020 and 2024? Three specific objectives structure the inquiry: (1) to document the quantitative evolution of labelled startups and ecosystem infrastructure; (2) to assess changes in startup funding and employment associated with the programme period; and (3) to evaluate Algeria's competitive trajectory within the North African and global startup landscape. Section 2 reviews the relevant literature; Section 3 presents the methodology; Section 4 analyses the results; Section 5 draws conclusions and policy implications.

2. Literature Review

2.1. Startup Ecosystems as Drivers of Economic Transformation

The concept of the startup ecosystem has become one of the most influential frameworks in contemporary entrepreneurship research. Following Moore's (1993) foundational ecological analogy, Isenberg (2010) formalised the ecosystem model as a multi-domain architecture spanning policy, finance, culture, human capital, markets, and support structures, all of which must align for a high-growth entrepreneurial environment to emerge. Stam (2015) refined this into the notion of an entrepreneurial ecosystem, defined as a set of interdependent actors and factors coordinated in such a way as to enable productive entrepreneurship within a particular territory. Audretsch and Thurik (2001) demonstrated that economies with more entrepreneurial dynamism exhibit higher rates of innovation diffusion and employment creation. Aghion, Akcigit and Howitt (2015) showed that entry by new innovative firms constitutes the primary mechanism through which knowledge externalities are realised in modern growth models. For resource-dependent economies such as Algeria's, the startup ecosystem represents a structurally important pathway towards the kind of knowledge-intensive diversification that traditional industrial policy has failed to deliver (World Bank, 2023).

2.2. Government Label and Certification Programmes: Theory and Evidence

Governments can intervene in startup ecosystems through multiple channels: direct subsidies, public procurement, regulatory simplification, incubation infrastructure, and label or certification schemes. Label programmes represent a particularly structured form of intervention in which the state formally identifies high-potential ventures and confers a differentiated set of benefits upon them. The logic is straightforward: information asymmetries prevent private capital markets from efficiently pricing early-stage innovative ventures (Lerner, 2009), and a credible government label can reduce this asymmetry by signalling quality and commitment to investors, clients, and partners. France's La French Tech label, launched in 2013, contributed to a measurable increase in startup formation and funding in certified ecosystems (Demmou & Stefanescu, 2019). Israel's technological incubator programme, extensively studied by Avnimelech and Teubal (2006), is widely credited with catalysing that country's emergence as a global innovation hub. South Korea's TIPS (Tech Incubator Programme for Startups) similarly combined private sector mentorship with public co-investment to accelerate

ecosystem maturation (OECD, 2016). However, Lerner (2009) warns that such programmes are vulnerable to political capture. Wallsten's (2000) additionality framework provides the methodological bridge: a programme is effective to the extent that it generates innovation activity that would not have occurred in its absence, without displacing equivalent private-sector investment.

2.3. The Algerian Startup Ecosystem: Prior Research

Academic research specifically focused on the Algerian startup context has grown rapidly since 2020 but remains concentrated in domestic journals and doctoral dissertations. Djekidel, Doua and Rais (2021) provided the first systematic legal analysis of the Startup Label framework, detailing the obligations and characteristics of labelled entities under Decree No. 20-254. Boumendil (2022) conducted a field study of 20 labelled startups and found that access to the ASF, while formally available, remained practically constrained by procedural complexity and collateral-equivalent requirements. Boukhelf (2023), in a doctoral dissertation at Université Mouloud Mammeri Tizi Ouzou, confirmed that financing remains the primary structural barrier for Algerian startups, with venture capital penetration far below the levels observed in Egypt. A review article published in the Revue Algérienne d'Economie de Gestion (Dris, 2024) characterised Algeria's startup ecosystem as a dynamic and booming landscape while identifying three systemic weaknesses: geographic concentration of ecosystem actors in the three largest cities, limited availability of late-stage capital, and an unresolved tension between the speed of regulatory innovation and the inertia of the banking sector. The present paper builds on these contributions by analysing the full arc of the programme's performance through 2024, using a multi-dimensional indicator framework not previously applied to this context.

3. Methodology

3.1. Research Design

This study adopts a descriptive-analytical research design with a longitudinal orientation, tracking changes in Algeria's entrepreneurial ecosystem across the period January 2020 to December 2024. The choice of a secondary data methodology is consistent with established practice in entrepreneurial ecosystem research (Stam, 2015; Mason & Brown, 2014), where aggregate ecosystem-level indicators are routinely constructed from publicly available administrative and institutional data. The study does not claim to establish strict causal relationships between the Startup Label and the outcomes observed; rather, it uses a before-after comparative framework to assess whether the introduction and scaling of the programme is consistent with ecosystem-level improvements across multiple indicators simultaneously.

3.2. Data Sources

Data were collected from six categories of source: (1) official legislative and regulatory texts: Executive Decree No. 20-254 (15 September 2020), Executive Decree No. 21-170 (28 April 2021), Executive Decree No. 23-323 (6 September 2023), Finance Laws 2020 and 2021, and the Journal Officiel de la République Algérienne; (2) official government communications: statements by Minister Yacine Oualid reported by the Agence de Presse Service (APS, October 2021), Algeria Invest (July 2024), and the Algeria Disrupt conference proceedings; (3) platform data: startup.dz; Tracxn (accessed 2024); and Jeune Afrique (March 2022); (4) international index data: StartupBlink Global Startup Ecosystem Index, editions 2021, 2023, and 2025; (5) market intelligence reports: Stats & Market Insights (2025) and AlgeriaTech (2025).

3.3. Key Performance Indicators

Five measurement dimensions are operationalised, following the framework of Mason and Brown (2014): (1) Ecosystem size, measured by the number of entities registered on startup.dz and the number holding the Startup Label; (2) Ecosystem infrastructure, measured by the count of active incubators and Entrepreneurship Development Centres (CDEs); (3) Financial attractiveness, measured by total startup funding raised; (4) Direct economic impact, measured by direct job creation attributed to startups; and (5) International competitiveness, measured by Algeria's rank in the StartupBlink Global Startup Ecosystem Index. Where possible, data are presented at annual resolution to reveal temporal trends.

3.4. Limitations

Three limitations merit explicit acknowledgement. First, causal attribution is inherently difficult: the growth observed between 2020 and 2024 may partly reflect broader structural trends, post-COVID entrepreneurial reorientation, and digital infrastructure investment that are independent of the Startup Label itself. Second, official Algerian statistics on startup employment and funding are not disaggregated by label status, making it impossible to isolate the contribution of labelled entities from the broader ecosystem. Third, the approval rate data available captures only a point in time and may not be representative of the full study period.

In addition, many of the indicators used in this study are derived from official institutional sources, government publications, and entrepreneurial ecosystem reports. While these sources provide valuable and consistent information on ecosystem development, they may not fully capture firm-level dynamics and performance heterogeneity among labelled startups.

These limitations are mitigated through triangulation across independent sources and by consistently distinguishing correlation from causation in the interpretation of results. Future research should complement secondary-source analysis with primary data collection directly from labelled startups. Such an approach would provide deeper insights into startup survival rates, revenue growth, scaling trajectories, access to investors and finance, and entrepreneurs' perceptions of the value and effectiveness of the Startup Label programme.

4. Results and Discussion

4.1. The Regulatory Architecture of the Startup Label Programme

Understanding the programme's impact requires first understanding its legal structure. Table 1 summarises the key legislative and regulatory instruments enacted between 2019 and 2025.

Table 1: Key Regulatory Instruments Governing the Startup Label Programme in Algeria (2019–2025)

Year	Legislative / Regulatory Instrument	Key Provision
2019	Law No. 19-14 (Finance Law 2020), Art. 69	3-year tax exemptions (TAP, IRG, IBS) for startups
Sept. 2020	Executive Decree No. 20-254 (15 Sept. 2020)	Creation of the National Labelling Committee; definition of Startup, Innovative Project and Incubator labels
Oct. 2020	Algeria Disrupt 2020 Conference	Launch of startup.dz platform (15 Oct.), A-Venture accelerator, and Algerian Startup Fund (ASF)
Nov. 2020	Executive Decree No. 20-356	Legal framework for A-Venture (Algeria Venture) support structure
2021	Finance Law 2021, Art. 86-87	Extension and reinforcement of tax exemptions for labelled startups and incubators
Apr. 2021	Executive Decree No. 21-170 (28 Apr. 2021)	Conditions for VAT exemption and 5% customs duty on equipment for labelled entities
Sept. 2023	Executive Decree No. 23-323 (6 Sept. 2023)	Restructuring of the labelling committee (renamed National Labelling Committee)
Dec. 2025	Executive Decree No. 25-311	Latest amendment clarifying renewal criteria and Scale-up label requirements

Source: Journal Officiel de la République Algérienne (2020, 2021, 2023, 2025); Algerie-eco (2020, 2023); Legal Doctrine (2021).

The regulatory sequence reveals a programmatic escalation of ambition. The initial fiscal exemptions introduced in the Finance Law for 2020 were intentionally modest, covering three years and restricted to tax exonerations, in order to gauge market response before committing larger public resources (Djekidel et al., 2021). The launch of the startup.dz platform on 15 October 2020 marked the operational start of the labelling system (Algerie-eco, 2020). By the Finance Law for 2021, the exemption period had been extended and the fiscal perimeter broadened; by 2023, the institutional architecture had been sufficiently consolidated to warrant a renaming of the labelling committee itself. The most recent amendment (Decree No. 25-311, December 2025) introduced a formal Scale-up label reserved for labelled startups that have achieved sustained revenue growth (TSA Algérie, 2025). A startup is defined under Algerian law as an Algerian-law company not more than eight years old, whose business model relies on innovative products, services, or business models, with a maximum of 250 employees and capital held at least 50% by natural persons or approved investment funds (Decree No. 20-254, Art. 11; Legal Doctrine, 2021).

This definition explicitly excludes lifestyle businesses, anchoring the label in genuine innovation, a design choice consistent with international best practice (Demmou & Stefanescu, 2019).

4.2. Quantitative Growth of the Ecosystem: 2020–2024

Table 2 presents the evolution of key ecosystem indicators across the study period, and Figure 1 illustrates the growth trajectory of registered and labelled startups.

Table 2: Evolution of Key Startup Ecosystem Indicators in Algeria (2020–2024)

Indicator	2020	2021	2022	2023–2024	Change
Registrations on startup.dz	~200	~700	3,516+	7,800+	+3,800%
Startups with Startup Label	~100	~480	751	2,300+	+2,200%
Applications submitted (cumul.)	--	~700	3,516	~7,000	--
Active incubators	14	29	60+	124	+786%
CDEs	0	0	~40	104	--
Jobs created (direct, cumul.)	--	~3,000	~8,000	20,000+	--
Total funding (USD)	~$50M	~$150M	~$406M	$650M	+60% (2024)
StartupBlink global rank	--	~180	~130	#111	↑ +7.2%
Africa rank (StartupBlink)	--	#6	#5	#4	↑

Source: APS (2021); Jeune Afrique (2022); Algeria Invest (2024); AlgeriaTech (2025); StartupBlink (2025); Stats & Market Insights (2025); Tracxn (2024).

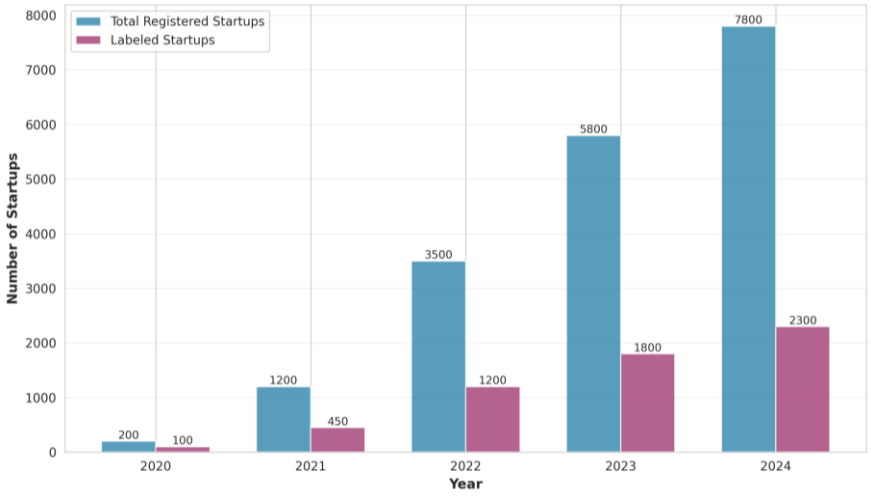

Figure 1: Growth of the Algerian Startup Ecosystem (2020–2024)
Source: startup.dz (2024); Algeria Invest (2024); APS (2021).

Registrations on startup.dz grew from an estimated 200 in 2020 to over 7,800 by 2024, an increase of approximately 3,800%. Of registered entities, 2,300 hold the formal Startup Label, representing a 228% growth in the labelled population between 2021 and 2023, as confirmed by Minister Yacine Oualid in a July 2024 television interview cited by Algeria Invest (2024). A particularly informative statistic, reported by Minister Oualid at the October 2021 regional conference in Constantine, is that 63% of all labelled startups then in existence had been created in the two years following the programme's launch (APS, 2021), suggesting that the increase in startups creation coincided with the implementation of the programme rather than merely reflecting the relabellingof existing entities. The approval rate tells a more sobering story. As of March 2022, Noureddine Ouadah, Director-General of the Startups Directorate, confirmed that only 751 of 3,516 cumulative applications, approximately 21.4%, had received the label (Jeune Afrique, 2022). This low approval rate reflects the stringency of the innovation criterion and the capacity constraints of the National Labelling Committee, which is legislatively mandated to convene only every two months (Decree No. 20-254, Art. 6). While a selective approach may improve programme quality, it also implies that a large number of innovative projects are denied access to the programme's benefits, a potential efficiency loss that future policy should address.

4.3. Infrastructure Expansion: Incubators and Support Structures

The most visible infrastructural achievement of the programme period is the rapid expansion of the incubator network. At the October 2021 Constantine conference, Minister Oualid reported that the number of active business incubators had doubled from 14 to 29 within the preceding six-month period (APS, 2021). By 2024, this figure had reached 124 university-linked incubators engaging an estimated 60,000 students in startup-oriented final-year projects (AlgeriaTech, 2025). Alongside these incubators, 104 Entrepreneurship Development Centres (Centres de Développement de l'Entrepreneuriat, CDEs) were established nationwide, collectively providing training and mentorship to 1,770 micro-enterprises in their first year of operation (Algeria Invest, 2024). Isenberg (2010) identifies the density and quality of mentorship networks as one of the most difficult-to-replicate components of a successful entrepreneurial ecosystem and one of the most consequential for early-stage firm survival. The rapid scaling of university-linked incubators is particularly notable in Algeria's case because it embeds entrepreneurship promotion within the existing higher education infrastructure, reducing marginal costs while addressing a documented skills gap in business creation competencies among STEM graduates (Boukhelf, 2023). Figure 2 illustrates the infrastructure development between 2020 and 2024.

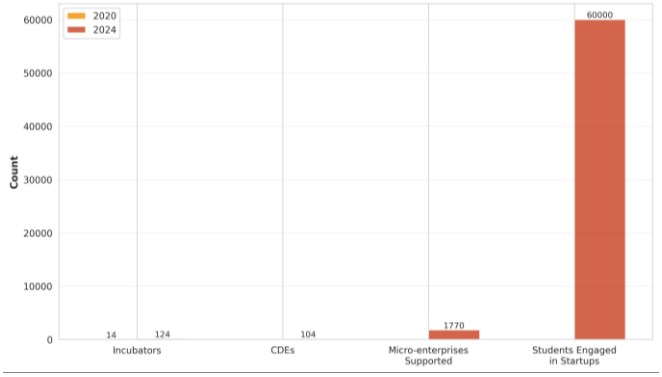

Figure 2: Infrastructure Development in Algeria's Startup Ecosystem
Source: AlgeriaTech (2025); Algeria Invest (2024); APS (2021).

4.4. Benefits of the Startup Label: A Structured Analysis

Table 3 provides a structured summary of the benefits conferred by the Startup Label, with explicit reference to the legal instruments establishing each provision.

Table 3: Benefits Conferred by the Algerian Startup Label and Their Legal Basis

Benefit	Description	Legal Basis
Tax Exemptions	Full exemption from TAP, IRG/IBS for 4 renewable years (extended from initial 3 years by Finance Law 2021)	Art. 69, LF 2020; Art. 86-87, LF 2021
VAT Exemption	Exemption from VAT on equipment purchases required for the startup's investment project	Decree No. 21-170, Art. 5
Customs Duty Reduction	Reduced customs rate of 5% on imported equipment (vs. standard rates of up to 30%)	Decree No. 21-170, Art. 6
IP Cost Coverage	State covers fees for patent registration and intellectual property protection (announced Feb. 2022)	Algeria Disrupt 2022 Conference
Access to ASF Financing	Eligibility for equity/quasi-equity investment from the Algerian Startup Fund (6 public banks, USD 411M committed)	Algeria Disrupt 2020; startup.dz
Public Procurement Priority	Preferential access to government tenders and contracts for labelled entities	Decree No. 20-254, Art. 11
Incubation & Acceleration	Free access to A-Venture accelerator network and 124 university-linked incubators (CDEs)	startup.dz (2024)
Foreign Currency Account	Authorisation to open foreign currency accounts to facilitate international transactions	Bank of Algeria Circular (2022)

Source: Decree No. 20-254 (2020); Decree No. 21-170 (2021); Finance Laws 2020 and 2021; Algeria Disrupt 2022 Conference (Algerie-eco, 2022); startup.dz (2024).

The benefit package represents a substantial reduction in the cost of firm formation and early-stage operation. The tax exemption alone, covering TAP, IRG/IBS, and VAT on equipment purchases, can represent a saving equivalent to 20–30% of early-year operating costs for a technology startup with positive revenue (Boumendil, 2022). The reduction of customs duties on imported equipment from rates of up to 30% to a fixed rate of 5% is particularly significant given Algeria's dependence on imported technology hardware. The Algerian Startup Fund (ASF), capitalised at an initial 1.2 billion Algerian dinars with a subsequent USD 411 million injection (Algerie-eco, 2020; startup.dz, 2024), operates as a public venture capital fund that takes minority equity stakes in labelled startups rather than extending debt. This design choice explicitly addresses the principal-agent problems identified by Lerner (2009) in government loan programmes: by sharing upside risk rather than merely transferring downside burden, the ASF aligns state and entrepreneur incentives in a manner closer to private-sector venture capital practice.

4.5. Financial Performance and Sectoral Distribution

Total startup funding raised in Algeria reached USD 650 million in 2024, representing a 60% increase relative to 2023 (Stats & Market Insights, 2025). Figure 3 illustrates the funding growth trajectory from 2020 to 2024, and Table 4 disaggregates the 2024 figure by sector. Figure 4 presents the sectoral distribution as a proportion of total funding.

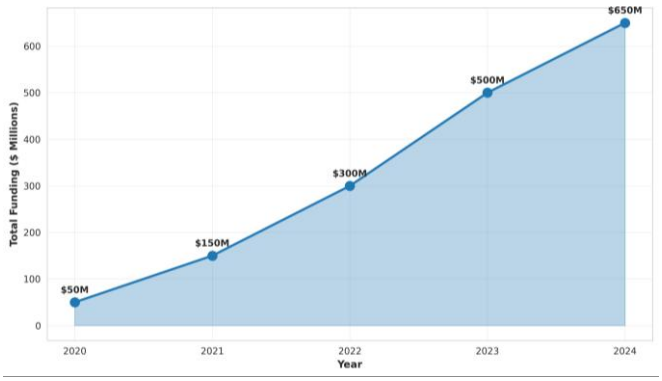

Figure 3: Total Startup Funding Growth in Algeria (2020–2024)
Source: Stats & Market Insights (2025); AlgeriaTech (2025).

Table 4: Sectoral Distribution of Startup Funding in Algeria (2024)

Sector	Funding Raised (2024)	% of Total
Financial Technology (Fintech)	$200 million	30.8%
Agricultural Technology (Agritech)	$180 million	27.7%
Green Technology (GreenTech)	$120 million	18.5%
E-commerce & Logistics	$100 million	15.4%
HealthTech & EdTech	$50 million	7.6%
TOTAL	**$650 million**	**100%**

Source: Stats & Market Insights (2025).

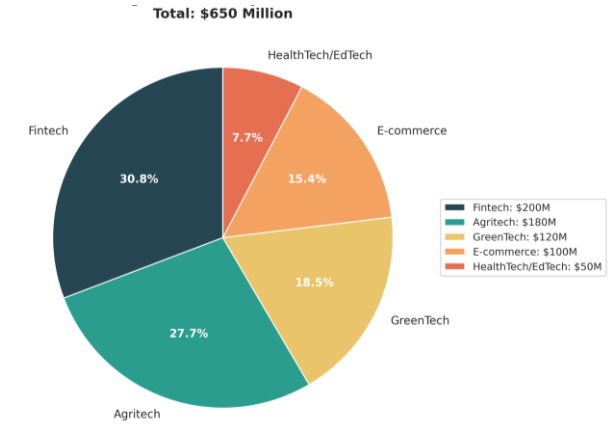

Figure 4: Funding Distribution by Sector, Algeria (2024)
Source: Stats & Market Insights (2025).

Fintech attracted the largest share at USD 200 million (30.8%), driven by the large unbanked population, estimated at over 60% of Algerian adults, and by regulatory openness following the National Financial Inclusion Strategy. Agritech followed with USD 180 million (27.7%), reflecting strategic government prioritisation of food security and smart farming. GreenTech raised USD 120 million (18.5%), aligned with Algeria's commitments under the 2030 National Energy Transition Plan (Stats & Market Insights, 2025). The flagship case study that anchors the programme's credibility internationally is Yassir, a ride-hailing and super-app startup founded in Algiers that raised USD 150 million in a Series B round in November 2022 led by BOND Capital, the largest single fundraising round by any Algerian company in history (AlgeriaTech, 2025). By 2024, Yassir reported 8 million users and 100,000 active drivers and merchants across 45 cities in six countries, illustrating the programme's wider ambition to produce scalable ventures capable of competing regionally and globally.

4.6. Employment Creation

Algerian startups created more than 20,000 direct jobs in 2024 (Stats & Market Insights, 2025). While this figure is modest relative to the formal employment market, its economic significance should be evaluated against its structural quality rather than its absolute scale. The jobs created are concentrated in sectors, fintech, artificial intelligence, and agritech, that are structurally absent from the hydrocarbon-dominated formal economy. They are also disproportionately filled by young university graduates (Dris, 2024), precisely the demographic most exposed to unemployment and emigration. TSA Algérie (2025) reports that 20% of all labelled startups were created by members of the Algerian diaspora, suggesting that the programme may be contributing to efforts aimed at reducing brain drain by creating high-quality domestic investment opportunities for internationally educated Algerians. Figure 5 illustrates the cumulative direct job creation trajectory across the study period.

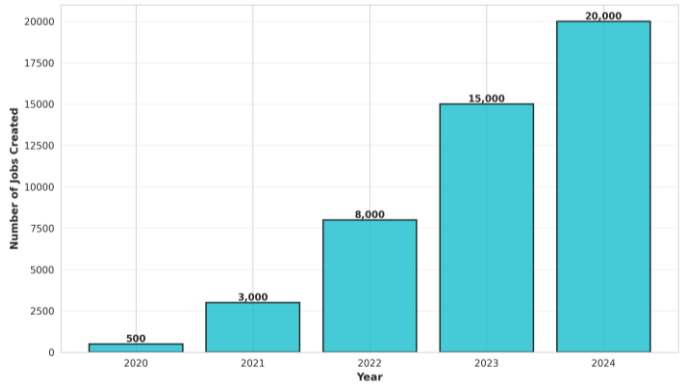

Figure 5: Direct Jobs Created in Labelled Startups (2020–2024)
Source: Stats & Market Insights (2025); APS (2021).

4.7. International Competitive Position

Table 5 situates Algeria within the North African startup landscape as of 2024. Figure 6 shows the trajectory of Algeria's global and regional rankings from 2020 to 2025.

Table 5: North African Startup Ecosystem Comparative Overview (2024)

Country	Global Rank	Africa Rank	Labelled/Active	Funding (2024)	Ecosystem Maturity
Algeria	#111	#4	2,300+	$650M	High: dedicated ministry, ASF fund, 124 incubators
Egypt	#66	#1	~5,000	$1.2B	High: Flat6Labs, EFG EV, Cairo ecosystem
Tunisia	#101	#3	~1,500	$210M	Medium: established VC culture, smaller market
Libya	--	--	< 100	< $10M	Low: political instability

Source: StartupBlink (2025); Stats & Market Insights (2025); Tracxn (2024); AlgeriaTech (2025). Data for comparator countries are approximate.

Figure 6: Algeria's Startup Ecosystem Ranking Improvement (2020–2025)
Source: StartupBlink (2021, 2023, 2025).

Algeria's position at #111 globally and #4 in North Africa represents a structural improvement from near-complete absence from global rankings in the pre-2020 period (Dris, 2024). The ecosystem grew at a rate of 7.2% in 2025, among the highest on the continent (StartupBlink, 2025). No African country improved its startup ecosystem ranking by a larger margin in the 2020–2024 period in absolute terms (StartupBlink, 2025). By the count of active labelled startups, Algeria now ranks second in Africa behind Nigeria (Tracxn, 2024), having overtaken more established ecosystems in Tunisia and Kenya. The persistence of the gap with Egypt, which ranks #66 globally and has attracted USD 1.2 billion in startup funding in 2024, reflects the structural advantages that a more mature financial sector, a larger consumer market, and a longer history of private equity activity confer upon the Egyptian ecosystem. Narrowing this gap will require progress on precisely those dimensions where Algeria's programme has been weakest: late-stage funding availability and the depth of the domestic venture capital talent pool (Boukhelf, 2023).

4.8. Persistent Structural Challenges

The evidence assembled above must be qualified by four structural constraints that remain unresolved as of the end of the study period. First, the label approval rate of 21.4% as of early 2022 indicates that the National Labelling Committee, which meets only every two months under the terms of Decree No. 20-254, is functioning as a bottleneck. The volume of applications grew far faster than the committee's institutional capacity, creating a backlog that deters applications and delays programme access. Second, the funding distribution is heavily concentrated at seed and Series A stages; Tracxn (2024) records only three Algerian startups at Series A or above as of 2024, and late-stage capital remains effectively unavailable domestically. Third, brain drain continues to represent a critical structural threat: the SNTN-2030 strategy's target of reducing tech talent emigration by 40%

implies an acknowledgement that the current rate is itself a constraint on ecosystem depth (AlgeriaTech, 2025). Fourth, geographic concentration remains a concern: the vast majority of labelled startups are based in Algiers, Oran, and Constantine (Jeune Afrique, 2022), leaving the country's remaining wilayas with limited ecosystem infrastructure.

4.9. Discussion in Light of Entrepreneurial Ecosystem Theory

The empirical findings of this study can be interpreted through the lens of entrepreneurial ecosystem theory presented earlier in the literature review. The substantial increase in the number of labelled startups, incubators, entrepreneurship development centres, and funding volumes is broadly consistent with Isenberg's (2010) argument that successful entrepreneurial ecosystems depend on the interaction of multiple reinforcing domains, including policy, finance, human capital, and support institutions. The rapid expansion of university-linked incubators and entrepreneurship support centres reflects the strengthening of ecosystem infrastructure and mentorship networks, which Isenberg identifies as critical components for entrepreneurial development and early-stage firm survival.

Similarly, the observed growth in startup funding and the establishment of the Algerian Startup Fund (ASF) are consistent with Stam's (2015) conceptualisation of entrepreneurial ecosystems as systems of interdependent actors and resources that facilitate productive entrepreneurship. Access to finance, institutional support, and knowledge-transfer mechanisms appear to have expanded simultaneously during the study period, suggesting a progressive consolidation of key ecosystem components.

The findings may also be interpreted in light of Lerner's (2009) argument that government intervention can help reduce information asymmetries affecting innovative startups. Through the Startup Label certification mechanism, the programme provides an institutional signal that may facilitate access to investors, financial support, and market opportunities. At the same time, the persistent challenges identified in this study, particularly the limited availability of late-stage funding, geographic concentration, and continuing brain drain, indicate that some ecosystem components remain underdeveloped, confirming Stam's (2015) view that entrepreneurial ecosystem performance depends on the balanced development of all ecosystem dimensions rather than on isolated policy interventions.

While the findings are broadly consistent with the theoretical expectations of entrepreneurial ecosystem theory, the study does not establish a direct causal relationship between the Startup Label programme and the observed outcomes. Rather, the results suggest that the implementation and scaling of the programme coincided with significant developments across several dimensions of Algeria's entrepreneurial ecosystem.

5. Conclusion

This paper has examined the impact of Algeria's Startup Label programme on the growth of the national entrepreneurial ecosystem between 2020 and 2024. The evidence is consistent across five independent measurement dimensions: the observed growth coincided with the implementation and scaling of the programme, including a rapid and sustained increase in ecosystem size (from ~200 to 7,800+ registrations; 2,300+ labelled entities; 228% growth between 2021 and 2023), a major expansion of supporting infrastructure (14 to 124 incubators; 104 CDEs established), a significant increase in financial attractiveness (USD 650 million in 2024, +60% year-on-year), meaningful employment creation (20,000+ direct jobs), and a measurable improvement in international competitiveness (#111 globally, #4 in North Africa, +7.2% growth). These developments are broadly consistent with the theoretical predictions of the entrepreneurial ecosystem literature (Isenberg, 2010; Stam, 2015) regarding the catalytic role of structured state support when it is accompanied by public venture capital and an expanding incubation network.

The programme's design strengths, a clear legal definition of startup status grounded in innovation criteria, a structured benefit package with explicit legal instruments, a public venture capital arm (ASF) that aligns state and entrepreneur incentives, and an accelerator network anchored in universities, distinguish it as one of the most coherent startup support architectures on the African continent. The diaspora participation rate of 20% is a particularly encouraging sign that the programme may be contributing to reducing the talent flows that have historically depleted Algeria's knowledge economy.

The programme confronts four structural challenges that will determine whether the current quantitative growth translates into lasting ecosystem quality. The low label approval rate (21.4% as of 2022) suggests institutional capacity constraints in the National Labelling Committee that require either procedural reform or a significant expansion of committee resources. The late-stage funding gap, the Series B cliff, cannot be addressed by the ASF

alone and will require the development of a domestic private venture capital industry, for which the 2022 regulatory opening on foreign ownership (abolition of the 51/49 rule) provides the necessary but not sufficient condition. Brain drain and geographic concentration represent systemic challenges that go beyond the Startup Label itself and require coordinated policy responses across education, infrastructure, and regional development. The contribution of this study is two-fold. Theoretically, it applies the entrepreneurial ecosystem framework to a context, a state-led knowledge economy transition in a resource-dependent North African economy, that has been significantly under-studied in the international literature. Empirically, it provides the first systematic multi-dimensional assessment of the Startup Label programme using data spanning its full operational period. While the findings suggest that the programme may have played an important role in ecosystem development, the study does not establish a direct causal relationship between the programme and the observed outcomes.Future research should extend this analysis through primary data collection directly targeting labelled startups, enabling rigorous measurement of additionality (Wallsten, 2000) and of the long-term survival and revenue growth rates of certified entities. Comparative analysis across the North African region would further illuminate the conditions under which label certification programmes of this type can most effectively catalyse entrepreneurial ecosystem development in emerging economies.

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Analitički pristup onlajn oglašavanju: formati, ciljanje publike i optimizacija troškova

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Apstrakt: Ovaj rad analizira ključne aspekte onlajn oglašavanja kao jednog od centralnih elemenata savremenog digitalnog marketinga. Fokus je na osnovnim karakteristikama onlajn oglašavanja, vrstama digitalnih oglasa, tehnikama ciljanja publike i upravljanju troškovima oglašivačkih kampanja. Razmatraju se različiti formati oglašavanja, uključujući prikazne, tekstualne, video, nativne i oglase na društvenim mrežama, kao i njihove specifične prednosti i ograničenja. Posebna pažnja posvećena je metodama ciljanja korisnika, kao što su demografsko, geografsko, interesno, kontekstualno, psihografsko i retargeting ciljanje, koje omogućavaju veću preciznost i efikasnost marketinških kampanja. Takođe, rad obrađuje strategije upravljanja troškovima oglašavanja kroz optimizaciju budžeta, A/B testiranje, analizu povrata na investiciju (ROI) i diversifikaciju kanala. Cilj rada je da prikaže kako savremene digitalne tehnologije omogućavaju efikasnije, merljivije i prilagodljivije marketinške aktivnosti u odnosu na tradicionalne oblike oglašavanja.

Ključne reči: onlajn oglašavanje, digitalni marketing, ciljanje publike, ROI, digitalni oglasi.

An Analytical Approach to Online Advertising: Formats, Audience Targeting, and Cost Optimization

Abstract: This paper analyzes key aspects of online advertising as a central component of modern digital marketing. The focus is placed on the fundamental characteristics of online advertising, types of digital advertisements, audience targeting techniques, and advertising cost management. Various advertising formats are examined, including display, text, video, native, and social media ads, along with their specific advantages and limitations. Special attention is given to user targeting methods such as demographic, geographic, interest-based, contextual, psychographic, and retargeting targeting, which enable greater precision and efficiency in marketing campaigns. The paper also discusses strategies for managing advertising costs through budget optimization, A/B testing, return on investment (ROI) analysis, and channel diversification. The aim of the paper is to demonstrate how modern digital technologies enable more efficient, measurable, and adaptable marketing activities compared to traditional advertising forms.

Keywords: online advertising, digital marketing, audience targeting, ROI, digital ads.

1. Introduction

In the contemporary digital economy, online advertising has become one of the most influential components of marketing communication strategies. The rapid development of internet technologies, mobile devices, and data analytics has fundamentally transformed the way organizations communicate with consumers. Unlike traditional media, digital advertising enables highly interactive, measurable, and data-driven communication, allowing marketers to optimize campaigns in real time and reach precisely defined audience segments (Chaffey & Ellis-Chadwick, 2019).

The evolution of online advertising is closely linked to the broader transformation of marketing into a data-centric discipline. Modern marketing systems increasingly rely on consumer data, behavioral tracking, and algorithmic decision-making to deliver personalized advertising experiences (Kannan & Li, 2017). This shift has enabled advertisers to move from mass communication strategies toward highly targeted and individualized messaging, significantly increasing efficiency and return on investment.

A key feature of digital advertising is its measurability. Unlike traditional media such as television or print, online platforms allow advertisers to track user interactions, impressions, clicks, conversions, and engagement in real

time. This capability has led to the widespread adoption of performance-based models such as pay-per-click (PPC) advertising, where costs are directly linked to user engagement rather than exposure (Ryan & Jones, 2009). As a result, advertising budgets can be more effectively allocated and continuously optimized.

Furthermore, the rise of social media platforms has introduced new forms of consumer engagement and brand communication. Platforms such as Facebook, Instagram, LinkedIn, and TikTok enable advertisers to combine content marketing with behavioral targeting, fostering two-way communication between brands and users (Kotler et al., 2016). This interactive environment has significantly increased the importance of personalization, relevance, and user experience in advertising design.

Another important development in online advertising is the use of big data analytics and automated targeting systems. Research shows that data-driven marketing strategies significantly improve campaign effectiveness by enabling precise segmentation and predictive modeling of consumer behavior (Wedel & Kannan, 2016). At the same time, concerns related to privacy, ad fatigue, and ad-blocking technologies present ongoing challenges for advertisers. Recent studies indicate that artificial intelligence is increasingly transforming online advertising through advanced personalization, predictive analytics, and automated campaign optimization. At the same time, researchers emphasize growing concerns regarding consumer privacy, transparency, and ethical use of personal data in digital advertising ecosystems (Reeyazati&Samizadeh, 2024; Saura, 2024).

Within this context, online advertising can be understood as a complex ecosystem that integrates various formats, channels, and targeting techniques. These include display advertising, search engine marketing, video advertising, social media advertising, and email marketing, all of which contribute to building integrated digital communication strategies. The effectiveness of these tools depends not only on creative execution but also on strategic targeting and cost management.

Research Problem and Objectives

Despite the growing importance of online advertising, existing literature often examines advertising formats, audience targeting techniques, and cost optimization strategies separately. The core research problem of this paper stems from this fragmented nature of the existing literature, which frequently isolates these core dimensions into separate discussions. This research addresses this gap by establishing a unified analytical framework that demonstrates their strategic interdependence, thereby providing a comprehensive overview of the relationships between advertising formats, targeting approaches, and cost management practices in contemporary digital marketing.

The primary objective of this study is to analyze and synthesize how contemporary digital technologies enable more efficient, measurable, and adaptive marketing activities compared to traditional advertising channels. To achieve this objective, the paper addresses the following research questions:

RQ1: How do different online advertising formats align with specific marketing objectives and stages of the consumer decision-making process?

RQ2: How do contemporary targeting techniques optimize campaign relevance, and how do they navigate the emerging challenges of consumer privacy?

RQ3: Which cost management strategies are critical for maximizing the return on investment (ROI) within highly competitive digital auction markets?

The theoretical contribution of this paper lies in synthesizing existing knowledge on online advertising and highlighting the interdependence between advertisement formats, targeting mechanisms, and budget optimization strategies. By integrating these dimensions, the study provides a broader understanding of how digital advertising effectiveness can be improved.

Methodology

To provide a rigorous and comprehensive overview, this paper employs a structured literature review methodology. The research synthesis was conducted using peer-reviewed academic articles, book chapters, and authoritative industry reports (such as the IAB revenue reports). Relevant literature was identified through systematic searches in academic databases including Google Scholar, Scopus, and Web of Science.

The search strategy combined key terms such as "online advertising," "digital marketing," "audience targeting," "cost optimization," and "ROI". The scope of the analyzed literature spans from 2008 to 2026, with a deliberate emphasis on recent publications (2020–2026) to accurately capture contemporary structural shifts, including the integration of artificial intelligence, programmatic automation, and evolving global data privacy frameworks.

Sources were selected based on their direct relevance to the intersection of digital ad formats, consumer behavior, and financial efficiency

2. General Overview of Online Advertising

Online advertising represents one of the most important segments of modern marketing, enabling companies to reach a global audience through various digital channels. This form of advertising differs significantly from traditional media due to its ability to provide precise audience targeting, real-time performance measurement, and continuous campaign optimization. The development of digital platforms and data-driven technologies has further strengthened the role of online advertising in integrated marketing communication systems (Chaffey & Ellis-Chadwick, 2019; Kannan & Li, 2017; Evans, 2009).

Online advertising encompasses a wide range of strategies, from display advertising and search engine marketing to social media and email marketing. These channels are increasingly integrated within omnichannel marketing strategies, where consistent messaging is delivered across multiple touchpoints (Lamberton & Stephen, 2016; Yadav & Pavlou, 2014).

Display advertising is one of the oldest forms of online advertising and includes banners, video ads, pop-up windows, and similar formats that appear across different websites. These ads are visually engaging and are often used to increase brand awareness or promote specific products or services (Sutherland, 2020). A key advantage of display advertising is the ability to reach precisely defined target groups based on interests, demographics, and behavioral data. However, ad-blocking technologies and banner blindness represent significant challenges for advertisers (Goldfarb & Tucker, 2011; Deighton & Kornfeld, 2009).

Search engine advertising, particularly through Google Ads, is a highly effective strategy that allows companies to appear in search results when users actively search for relevant products or services. This intent-driven nature makes search advertising one of the highest-converting digital channels (Ryan & Jones, 2009; Li & Kannan, 2014). Payment is typically based on a pay-per-click (PPC) model, enabling advertisers to optimize costs and measure return on investment (ROI) more accurately. However, increasing competition for keywords has led to rising acquisition costs in many industries (Chaffey & Ellis-Chadwick, 2019).

Social media platforms such as Facebook, Instagram, Twitter, and LinkedIn have become indispensable channels for online advertising. These platforms enable advertisers to leverage advanced targeting capabilities based on user behavior, interests, and social interactions. Social media advertising is particularly effective for building engagement and brand loyalty due to its interactive and participatory nature (Kaplan & Haenlein, 2010; Dehghani & Tumer, 2015; Smith, 2011). Formats such as video ads, carousel ads, and sponsored content allow for highly creative communication strategies, while personalization significantly increases user response rates (Arora et al., 2008; Tucker, 2014).

Email marketing remains a powerful tool for direct and personalized communication with consumers. Despite being one of the oldest digital marketing channels, it continues to demonstrate high effectiveness when combined with segmentation and automation techniques. Personalized email campaigns significantly improve customer engagement and conversion rates (Chaffey & Ellis-Chadwick, 2019). However, challenges such as spam filtering and content relevance require continuous optimization of messaging strategies.

Overall, online advertising is increasingly shaped by data analytics, artificial intelligence, and automation technologies, which enable more precise targeting and improved campaign efficiency. The integration of these technologies has transformed online advertising into a highly dynamic and measurable marketing system (Wedel & Kannan, 2016; Dwivedi et al., 2021; Hoffman & Novak, 2018).

3. Types of Online Advertisements

Online advertisements have become an essential part of digital marketing, enabling brands to reach broader audiences through various digital platforms (Fennis & Stroebe, 2020). There are several main types of online ads, each with distinct characteristics and advantages, allowing advertisers to tailor campaigns according to their objectives and the needs of their target audience.

Display ads are one of the most common formats of online advertising (Lina & Ahluwalia, 2021). These ads appear on websites in the form of banners, images, videos, or interactive content. They are designed to attract users' attention while browsing different websites and may be placed in various positions on a page, such as headers, sidebars, or within the main content area (Lina & Ahluwalia, 2021). Their primary purpose is to increase brand awareness or promote specific products and services. A key advantage of display ads is their strong visual

appeal, and their effectiveness can be further enhanced through interest- or behavior-based targeting (Fennis & Stroebe, 2020).

Text ads are a simpler form of advertising and are commonly used within search engine results such as Google. These ads consist solely of text and typically include a headline, a short description, and a link to a landing page. Text ads are highly effective when combined with a pay-per-click (PPC) model, where advertisers pay only when users click on the ad (Lina & Ahluwalia, 2021). Their key advantage lies in relevance, as they are shown to users actively searching for related products or services, thereby increasing conversion rates and providing strong return on investment.

Video advertising has become increasingly popular due to the growth of platforms such as YouTube, TikTok, and social media networks that support video content sharing. Video ads are highly effective because they can convey complex messages and emotions in ways that are difficult to achieve with text or static visuals. They may be displayed before, during, or after video content, or as standalone ads on social media and other digital platforms (Lina & Ahluwalia, 2021). Video ads are particularly effective for brand building and user engagement; however, their production often requires greater resources compared to other ad types.

Social media ads are specifically designed for platforms such as Facebook, Instagram, LinkedIn, Twitter, and TikTok. These ads may include images, videos, carousels, or interactive elements such as polls and quizzes. Social media platforms enable precise targeting based on demographic data, interests, and user behavior, making these ads highly effective for achieving specific marketing objectives (Lina & Ahluwalia, 2021). In addition, they allow two-way communication, which further increases user engagement and fosters a sense of community around the brand.

Native advertising refers to a type of advertisement that blends naturally into the content of the page on which it appears (Lina & Ahluwalia, 2021). These ads resemble editorial content, which reduces user resistance and increases the likelihood of engagement (Fennis & Stroebe, 2020). Native ads are commonly used on news portals, blogs, and social media platforms, and may include text, images, or video content. Their main advantage lies in their subtlety and high relevance, as they are often tailored to the topic and tone of the surrounding content.

Pop-up and pop-under ads represent a more intrusive form of online advertising, appearing in separate windows above or below the current webpage. Although designed to attract user attention, they are often perceived as annoying, which may negatively affect brand perception. While they can achieve high visibility, their effectiveness largely depends on context and design quality.

Table 1: Types of Online Advertisements

Platform	Main Strength	Main Limitation	Best Marketing Objective
Google Ads	High purchase intent	High CPC in competitive industries	Conversions
Facebook	Detailed audience targeting	Declining organic reach	Awareness and engagement
Instagram	Visual storytelling	High content production requirements	Brand building
LinkedIn	Professional audience	Higher advertising costs	B2B marketing
TikTok	High engagement rates	Short content lifespan	Brand awareness and viral campaigns
YouTube	Strong video impact	Higher production costs	Awareness and education

Table 1 demonstrates that different digital advertising platforms possess distinct advantages and limitations, making them suitable for different marketing objectives. Google Ads is particularly effective for conversion-oriented campaigns because it targets users with explicit purchase intentions. However, increasing competition for keywords often leads to higher advertising costs. Social media platforms such as Facebook and Instagram offer advanced audience segmentation and strong engagement opportunities, but they require continuous content creation and optimization. LinkedIn is especially valuable for B2B marketing due to its professional user base, although advertising costs tend to be higher compared to other social networks. TikTok provides exceptional opportunities for organic reach and user engagement, particularly among younger audiences, but the short lifecycle of content may limit long-term campaign effectiveness. Finally, YouTube enables highly impactful video-based communication and educational content, although successful campaigns frequently require greater

production investments. These differences indicate that platform selection should be aligned with specific marketing objectives, target audience characteristics, and available budget resources.

4. Targeting in Online Advertising

Targeting in online advertising is a key strategy that enables advertisers to reach specific groups of users, thereby increasing the relevance and effectiveness of campaigns. Instead of displaying ads to broad and non-selective audiences, advertisers use various targeting techniques to precisely define who will see their ads (Fennis & Stroebe, 2020; Kotler et al., 2016). This personalization contributes to higher user engagement, improved conversion rates, and optimized advertising costs (Chaffey & Ellis-Chadwick, 2019).

One of the basic forms of targeting is demographic targeting, which allows advertisers to reach users based on demographic characteristics such as age, gender, education, occupation, and income. Luxury brands may target high-income users, while youth-oriented products are directed toward younger demographic groups (Quesenberry, 2020; Kotler et al., 2016). Demographic targeting is particularly useful for brands with clearly defined audience segments.Geographic targeting enables advertisers to display ads based on users' physical location (Fennis & Stroebe, 2020). This can range from global and regional targeting to country, city, or even neighborhood level. Local businesses such as shops or restaurants can target users in their immediate surroundings to attract nearby customers (Chaffey & Ellis-Chadwick, 2019). Geographic segmentation remains one of the most practical forms of targeting in location-based marketing.

Interest-based targeting is one of the most precise methods, relying on data about users' preferences and online activities. Advertisers use data from social media, search engines, website visits, and other digital interactions to identify user interests (Fennis & Stroebe, 2020; Wedel & Kannan, 2016). This enables highly personalized campaigns that increase engagement and conversion probability through behavioral data analysis.

Contextual targeting is based on the content of the webpage where the ad is displayed. Algorithms analyze webpage content and match it with relevant advertisements (Quesenberry, 2020). For example, travel insurance ads may appear on pages related to tourism. This approach is effective because users are already engaged with relevant content, increasing the likelihood of interaction.

Remarketing (retargeting) is an advanced targeting technique that allows advertisers to reach users who have previously interacted with a brand but did not complete a desired action. If a user visits an online store and views a product without purchasing it, ads for that product may later appear while browsing other websites (Chaffey & Ellis-Chadwick, 2019; Fennis & Stroebe, 2020). This method is highly effective due to prior user interest and behavioral intent signals.Psychographic targeting focuses on psychological characteristics such as values, attitudes, lifestyle, and personal preferences. It is used for highly personalized campaigns that address emotional and psychological needs of users. For example, environmentally conscious consumers may be targeted with messages emphasizing sustainability (Kotler et al., 2016). This form of targeting reflects the increasing importance of consumer psychology in digital marketing strategies.

Device-based targeting allows advertisers to deliver ads based on the type of device used, such as mobile phones, tablets, desktops, or smart TVs (Fennis & Stroebe, 2020). Mobile ads often require shorter and more concise messages, while desktop ads can include more detailed content and richer visuals. With the growth of mobile-first internet usage, device-based segmentation has become a critical optimization factor (Ryan & Jones, 2009).

Overall, targeting is essential for achieving high relevance and campaign efficiency in online advertising, significantly improving engagement, reducing costs, and increasing return on investment (ROI) (Chaffey & Ellis-Chadwick, 2019; Wedel & Kannan, 2016).

Empirical Findings on Consumer Behavior and Advertising Efficacy

To transition from a purely descriptive theoretical overview to an empirically grounded synthesis, it is necessary to examine how these targeting methods and formats perform in real-world contexts. Over the past decade, numerous researchers have empirically tested the direct impact of personalized digital advertising on consumer behavior, engagement metrics, and psychological resistance. Table 2 provides a structured synthesis of prominent empirical studies, mapping their methodological foundations to their core findings regarding consumer responses.

Table 2: Synthesis of Key Empirical Research on Consumer Behavior and Digital Advertising

Author(s) & Year	Key Criteria / Focus Area	Research Method / Context	Core Empirical Findings & Impact on Consumer Behavior
Tucker (2014)	Privacy controls & Personalized ad responsiveness	Field experiment on social networks	Granting users proactive privacy controls over their data significantly increases the click-through rates (CTR) of personalized ads, as it reduces consumer perceived risk.
Li & Kannan (2014)	Multi-channel attribution & Conversion behavior	Quantitative tracking data in online environments	Consumers do not convert linearly; different channels (search vs. display) hold varying touchpoint values. Text-based search engine ads capture active intent and yield the highest direct conversion probability.
Lina & Ahluwalia (2021)	Personalized ads & Social commerce impulse buying	Quantitative empirical survey on social commerce platforms	High relevance in personalized social ads triggers a psychological state of "flow experience" in consumers, which directly accelerates impulse buying behaviors on social platforms.
Leszczynska& Baltag (2024)	Data sharing willingness for personalization	Empirical consumer survey and behavioral tracking	Confirms the "privacy paradox"—consumers demand highly non-personalized alternatives unless a direct, transparent value-added benefit is visibly demonstrated by the brand.
Yildirim &Gündüzyeli (2026)	AI programmatic ads & Sustainability	Mixed-methods empirical evaluation of AI targeting ecosystems	Advanced AI algorithmic targeting vastly improves real-time consumer engagement levels, but rapidly induces severe ad fatigue if consumers perceive a total loss of tracking transparency.

Source: Author's synthesis based on referenced literature.

As synthesized in Table 2, the empirical data explicitly shows that digital advertising efficacy is a dynamic equilibrium. When ad formats are perfectly aligned with consumer psychology, such as generating a "flow experience" through highly visual personalized social commerce ads, they directly stimulate consumer purchasing actions and impulse buying. However, the data also warns that when tracking mechanisms cross ethical thresholds without consumer-controlled filters, ad fatigue and structural privacy pushback immediately degrade campaign return on investment.

5. Advertising Cost Management

Advertising cost management is a crucial component of a successful marketing strategy, enabling companies to efficiently allocate resources and maximize return on investment (ROI). In the digital environment, where numerous tools are available for performance tracking and analysis, careful planning, monitoring, and optimization of advertising costs has become increasingly important (Tillberg et al., 2020).

The first step in cost management is setting clear objectives and budgets. Advertisers must define whether the goal is brand awareness, lead generation, or sales growth, and allocate funds accordingly. Establishing a realistic budget helps prevent overspending and ensures financial sustainability (Tillberg et al., 2020).

One of the most important aspects of cost management is ROI tracking (Sutherland, 2020). ROI represents the ratio between revenue generated and advertising expenditure. Digital marketing tools such as Google Analytics and Facebook Ads Manager allow precise measurement of campaign performance. Based on ROI data, advertisers can identify the most effective channels and allocate resources accordingly.

Budget optimization is another key strategy, involving continuous adjustment of spending to maximize efficiency. In PPC campaigns, keyword performance can be analyzed and bids adjusted to focus on high-performing keywords (Tillberg et al., 2020). Similarly, social media campaigns can be optimized by adjusting audience targeting, timing, and ad creatives.

Channel diversification is also important, as it reduces risk and increases reach by distributing budgets across multiple platforms such as search engines, social media, email marketing, and display networks. This allows advertisers to test different strategies and identify the most effective ones.

A/B testing is widely used to optimize advertising performance by comparing different versions of ads, headlines, calls to action, or visuals. This helps identify which version generates better engagement and conversions, allowing resources to be directed toward more effective ads (Sutherland, 2020).

Seasonal trend analysis is another important aspect of cost management. During peak shopping periods, budgets may be increased to capture higher demand, while in off-peak periods, spending may be reduced to maintain efficiency (Sutherland, 2020).

Finally, collaboration with external partners such as digital marketing agencies can provide additional expertise and tools for cost optimization (Tillberg et al., 2020). However, careful selection of partners is necessary to ensure alignment with brand objectives.

Through careful planning, continuous monitoring, and optimization, advertising cost management becomes an effective process that enables brands to maximize resources and achieve desired marketing outcomes.

6. Discussion

The analysis indicates that online advertising represents one of the most effective and dynamic components of contemporary marketing communication. Its primary advantage over traditional media lies in its ability to enable precise audience targeting, real-time performance measurement, and flexible campaign optimization. These characteristics significantly contribute to improved marketing efficiency and higher return on investment (ROI), which is consistent with findings in digital marketing literature.

The examination of different online advertising formats shows that each type serves a distinct role within an integrated marketing strategy. Display advertising is particularly effective in the awareness stage, where the primary objective is brand visibility. In contrast, text-based ads are more effective in capturing users with high purchase intent, resulting in higher conversion rates. Video advertising and social media ads contribute strongly to emotional engagement and brand interaction, while native advertising reduces user resistance by blending seamlessly into editorial content.

The findings also highlight the critical importance of targeting strategies in determining campaign success. Techniques such as demographic, geographic, interest-based, and contextual targeting allow for high levels of personalization, while remarketing further enhances conversion potential by re-engaging users who have already interacted with a brand. These approaches demonstrate the growing importance of data-driven decision-making in digital marketing, where behavioral and psychographic data play a central role in shaping advertising strategies. Although personalized advertising generally improves campaign effectiveness, recent studies indicate that excessive reliance on consumer data may generate privacy concerns and reduce consumer trust. This phenomenon, often referred to as the personalization–privacy paradox, represents one of the most significant challenges for contemporary digital advertising strategies (Saura, 2024; Kumar, 2025; Leszczynska et al., 2024). This data-centric paradigm is increasingly constrained by structural market shifts and consumer pushback. Recent empirical evidence highlights that the rapid deployment of artificial intelligence and automated programmatic algorithms has vastly improved targeting accuracy and campaign automation. However, these developments have simultaneously intensified global debates regarding algorithmic transparency, consumer autonomy, and the long-term sustainability of highly personalized advertising systems (Reeyazati&Samizadeh, 2024; Yildirim &Gündüzyeli, 2026).

On a macroeconomic level, sophisticated targeting technologies are no longer just marketing tools; they actively reshape competitive dynamics and contribute to market concentration, creating complex challenges and structural changes for both consumer welfare and overall market efficiency (Pepall& Richards, 2025). Therefore, modern campaign sustainability strictly depends on finding a strategic equilibrium between tracking precision and ethical data boundaries.

Furthermore, the effectiveness of online advertising is increasingly challenged by strict privacy regulations, consumer resistance to tracking technologies, and the growing adoption of ad-blocking software. Another critical limitation identified in the literature is the increasing saturation of digital channels. As competition intensifies within search engine and social media markets, advertising costs continue to rise, particularly cost-per-click (CPC) rates. Consequently, organizations must actively balance targeting precision with cost efficiency through tools like PPC optimization and continuous A/B testing to maintain sustainable campaign performance.

From a theoretical perspective, this paper contributes to the digital marketing literature by integrating advertising formats, audience targeting strategies, and cost optimization mechanisms into a single analytical framework. Such an approach enables a more comprehensive understanding of online advertising effectiveness in contemporary

digital environments. Overall, online advertising functions as a complex and highly integrated system that requires a strategic combination of formats, channels, and targeting techniques in order to achieve optimal performance.

7. Conclusion

This paper analyzed the key aspects of online advertising, including its main forms, types of digital advertisements, audience targeting strategies, and cost management approaches. Based on the analysis, it can be concluded that online advertising is one of the most efficient tools in modern marketing due to its ability to deliver precise targeting, measurable outcomes, and flexible campaign optimization.

By synthesizing the existing literature, this paper provides concrete answers to the established research questions: In response to RQ1, different ad formats function as highly complementary components within the marketing funnel: video and social formats drive top-of-funnel emotional engagement and awareness, whereas text-based search ads are uniquely capable of capturing immediate purchasing intent and driving bottom-of-funnel conversions. Regarding RQ2, while advanced targeting models drastically improve campaign relevance, their ultimate efficacy is bottlenecked by the personalization–privacy paradox; sustainability requires brands to adopt transparent data practices and balance behavioral tracking with less intrusive methods like contextual targeting. Finally, addressing RQ3, cost optimization cannot rely on static budget cuts; instead, it demands dynamic, real-time strategies, such as continuous A/B testing and diversified channel allocation—to mitigate the financial pressures of rising cost-per-click (CPC) rates in saturated digital auctions. Despite its substantial advantages in budget optimization and ROI maximization, online advertising faces intensifying challenges, including digital market saturation, surging advertising costs, and strict structural constraints regarding data privacy and user tracking. In conclusion, the future development of online advertising is expected to be increasingly driven by advanced analytics, automation, and artificial intelligence, which will further enhance its efficiency and complexity. For marketing professionals, continuous adaptation to these technological, regulatory, and strategic changes will be essential for maintaining competitiveness and sustainable performance in the contemporary digital environment.

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