



UNIVERSITY OF NATIONAL AND WORLD ECONOMY

The Spirit Makes The Power

**15TH INTERNATIONAL CONFERENCE ON APPLICATION OF
INFORMATION AND COMMUNICATION TECHNOLOGY AND
STATISTICS IN ECONOMY AND EDUCATION
ICAICTSEE – 2025**

October 9 - 11, 2025

***University of National and World Economy
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Dear Colleagues,

*On behalf of the Conference Committees I have the honor and pleasure to thank you all for your true participation in the work of the **15th International Conference on Application of Information and Communication Technology and Statistics in Economy and Education (ICAICTSEE-2025)**, <http://icaictsee.unwe.bg/>, which took place on October 9 - 11, 2025 at the University of National and World Economy (UNWE), Sofia, Bulgaria.*

I would like specially to express my gratitude to all of the program committee members for their genuine support without which it would never had happened.

Due to the current state of scientific development in all spheres of human activity, the constant knowledge and skill actualization of the academia and researchers in the field of Information and Communication Technology (ICT) is an obligatory necessity, especially when the world is in a global economic and financial crisis. The definition of long-term scientific research tasks in this area has a strategic importance, which is even truer for young researchers, lecturers and Ph.D. students.

The conference aims were conducting analysis of the current problems and presenting results of the ICT application in different areas of economy, education and related areas of scientific knowledge; outlining the existing possibilities for the application of modern ICT tools, methods, methodologies and information systems in economy and education; discussing advanced and emerging research trends with a long-term importance in the field of ICT application in economy and education.

The conference has established an academic environment that fosters the dialogue and exchange of ideas between different levels of academic and research communities.

*Dimitar G. Velev
ICAICTSEE-2025 Chair*

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Ontology of Software Abuse

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Abstract. The problem of classification and identification of software abuse does not lose its relevance. The aim of this paper is to present the evolution of software abuse based on historical and technological context and ontology formation. A review of the works of leading experts in the following areas is presented: computer viruses, computer attacks, threats to mobile devices and AI for Science. The authors analyse the composition of malicious programs, identifying such groups as Virus, Worm, Trojan, Botnet, Ransomware and others. Special attention is paid to the study of stages in the process of malware evolution and the formation of a set of service models such as Cybercrime-as-a-Service, Ransomware-as-a-Service and others. It is noted that the development of malware is directly related to the formation and functioning of the shadow digital economy.

Keywords. Soft Abuse, Computer Virus, Ontology, Malware, Vulnerabilities, Worm, Attack

1. Introduction

To define corporate sustainability is not an easy task. Even till now terms like CSR (Corporate social responsibility) and corporate citizenship are continue widely to be used. Nowadays, however, all these concepts are replaced by the broader term corporate sustainability. In the beginning it was not customary to define sustainability at corporate level.

The purpose of this report is to review the most common concepts of corporate sustainability in order to outline basic qualitative aspects of the most popular views. The ultimate goal is to find promising directions for building quantitative models of corporate sustainability at a later stage.

The most significant consideration is that these quantitative models had to be built on the basis of information available to the organization. This is information that is collected on a daily basis in corporate databases as a result of current activities.

2. Problem Statement

The authors set the goal of analyzing the emergence and development of software abuse (SA). This study covers a long period of development, taking into account their organization, the structure of their logical mechanisms, the purposes of their implementation and distribution, and methods of countering them.

Our research does not begin with an attempt to establish the authorship of SA, but rather by identifying the main sources of information. Unfortunately, history has not preserved the names of the developers (with rare exceptions – the Morris worm and the Brain computer

virus) or the specific conditions under which SA ideas were implemented, written, tested, and distributed. It should be emphasized that the practice of studying specific SAs shows that analysts and virologists are only confronted with the results of the implementation of internal mechanisms, that is, the final phase of the life cycle. All previous stages of the life cycle (including planning, requirements analysis, design, development, testing, implementation, and maintenance) remain completely inaccessible to researchers. Therefore, the main task is to create conditions for the formation of a software ontology – a formalized knowledge system that describes the methods of malicious use of software (standard and modified or specialized) in order to cause damage to the user or the information system.

During the preparation of this material, a debate arose regarding the use of two terms – ontology [1] and taxonomy [2], as they are frequently used in publications devoted to information technology. The choice fell on ontology, as a system for formally describing a domain of knowledge, categorizing viruses, their behavior, and relationships, as opposed to a simple hierarchy – taxonomy.

This material is based on the historical and technological context that characterizes the evolution of software – from the boot virus to the creation of service platforms and a specialized ecosystem.

3. Related Work

Most cybersecurity experts agree on the origins of computer viruses. Fred Cohen and his dissertation "Computer Viruses" (1986), as well as his earlier works [3], [4], [5], are considered the most influential.

A vast number of works have been devoted to the problems of describing the mechanisms of implementation and means of countering computer viruses. Among them, the leading authors, grouped into the following categories, should be highlighted:

1). Computer Viruses: Nikolai Bezrukov [6], Serghei Ohrimenco [7], Monnappa K. A. [8], P Fites, P Johnston and M Kratz [9], J. Parikka [10], P. Szor [11], J. Aycock [12], M. Cristodorescu [13], Sushi Jajodia [14], and others. It should be noted that the selection is difficult due to the large number of publications, and the list includes only the most representative ones. For example, books by N. Bezrukov and S. Ohrimenco were the first published in the USSR and largely determined the development of virology. Of particular note is the fundamental book by R. Burger [15], which provided the training and education for the first virologists and information security specialists.

2). Computer Attacks: Jakobsson, M., & Ramzan, Z. [16], Sotiropoulos, J. [17].

3). Threats to Mobile Devices: Misra, A., & Dubey, A. [18].

4). Recently, a new scientific and practical field has emerged – AI for Science, which utilizes artificial intelligence methods, machine learning models, and other components to create powerful security tools. These include: automated detection and response (SOAR/EDR), behavioral analysis, combating phishing and deepfakes, proactive threat hunting, etc. The main publications are the following: A. Hassan et al. [19], Khambam, S. K. R. et al. [20].

The work of renowned Bulgarian expert Dr. Veselin Bonchev [21], a pioneer of computer virology in Bulgaria and head of the first Computer Virology Laboratory at the Bulgarian Academy of Sciences, deserves special mention. His regular column and publications in Computers & Security magazine, which presented detailed characteristics of computer viruses, classifications of their destructive actions, and countermeasures, are also noteworthy. For that time (the mid- and late 1980s), this material was highly relevant and in demand.

We also consider it necessary to provide examples of ontologies. These include the following: Cybersecurity Ontology - The Relationship between Vulnerabilities, Standards, Legal, and Regulatory Requirements [22], A Milestone in Cybersecurity Ontology [23], Cyber Domain Ontology [24], The Design and Application of a Unified Ontology for Cyber Security [25], Cybersecurity Ontology for Dynamic Analysis of IT Systems [26], An Ontology-Based Cybersecurity Framework for AI-Enabled Systems and Applications [27].

An important aspect is a historical perspective on the field under study. January 2026 marked the 40th anniversary of the appearance of the "Amvi Brothers Virus" or Brain (also known as the Pakistani Brain or Lahore Brain). This was the first virus in history targeting the IBM PC. The virus infected the boot sector of five-inch floppy disks, slowing down the drive and occupying 7 kilobytes of RAM, making it inaccessible to the DOS system. The virus code included the real names, addresses, and phone numbers of the brothers who developed it, so that victims could contact them for "vaccination".

4. Methodology

The material in this article is based on an analysis of the available literature and a structural synthesis of data aimed at identifying and addressing problems related to the definition and classification of software abuse.

The methodological approach includes the following steps:

- formation of the research framework. This structure is derived from the specifics of the problem under study and a set of key questions, including characteristics and definitions of software abuses, their groups and types by purpose and triggering mechanisms;
- literature review. This study used the methodology of systematic historical review of scientific and practical literature, to synthesize existing knowledge and identify new trends related to the development of new groups of software abuses, whose activities are based on aggregation with topical components - artificial intelligence, machine learning, etc.;
- data analysis and synthesis. All collected data were systematized into thematic areas: historical stages of development of computer virology, principles of virus propagation, new types and mechanisms of implementation.

5. Results and Discussion

The four horsemen of the Apocalypse have been identified by the UN Secretary-General as the main threats to humanity: Geostrategic Tensions, Climate Change, Growing Mistrust at the Global level and the Danger of new Technologies. Speaking to delegates of the UN General Assembly, António Guterres outlined his priorities for 2020 [28]. In his report, he highlights a section entitled 'The "Flip Side" of the digital revolution', in which he points out that new technologies are developing so fast that we do not have time not only to react to them, but sometimes even to understand their essence. While they offered great benefits, digital technologies and artificial intelligence were becoming a tool for incitement, misinformation, interference with privacy, exploitation and crime. Thus, he considers unacceptable the use of autonomous combat systems - 'machines capable of killing without any human involvement and without any responsibility' - and calls for a ban on the use of 'Killer Robots'.

A.Guterres urged to restore order in cyberspace, which he called the digital 'Wild West'. "Terrorists, white supremacists and others like them abuse the Internet and social media," the UN chief said. - Bots spread misinformation, push polarisation and undermine democracy. Cybercrime will cost us \$6 trillion next year".

Another front to combat the costs of new technologies is the labour market, where A.Guterres predicts that automation will put hundreds of millions of workers out of work over

the next decade. He sees a way out in reforming the education system to teach people to be lifelong learners. According to the Secretary-General, the UN is the most appropriate platform for governments, the private sector, and civil society to counter the digital divide with global co-operation.

Fifteen years before this speech, Aycock J. [12] had identified four key threats - the four horsemen of the electronic Apocalypse -. Spam, Bugs, Denials of Service, and Malicious Software, which are summarised in the following figure.

FOUR HORSEMEN OF THE ELECTRONIC APOCALYPSE:



Fig.1 Four Horsemen of the Electronic Apocalypse, [©Siran Maxim 2025]

Malware is a broad term that refers to different types of malicious software such as viruses, worms, and rootkits. While performing malware analysis, experts come across different types of malware; some of them are classified based on their functionality and attack vectors:

- Virus or Worm: malware capable of copying itself and spreading to other computers. A virus requires user intervention, while a worm can spread without user intervention;
- Trojan: malware that masquerades as a regular programme to trick users into installing it on their systems. Once installed, it can perform malicious activities such as stealing sensitive data, uploading files to the attacker's server, or monitoring webcams;
- Backdoor/remote access Trojan (RAT): this is a type of Trojan that allows an attacker to access and execute commands on a compromised system;
- Adware: malware that displays unwanted adverts to the user. It is usually delivered via freeware downloads and can force software installation;
- Botnet: a group of computers infected with the same malware (called bots) waiting to receive instructions from a command and control server controlled by the attacker. The attacker can then send commands to these bots, which can perform malicious actions such as DDOS attacks or sending spam emails;
- information stealer: malware designed to steal sensitive data such as bank credentials or keystrokes from an infected system. Some examples of this malware include keyloggers, spyware, sniffers and form-grabbers;
- Ransomware virus: malware that holds a system to ransom by locking users out of their computer or by encrypting their files;

- Rootkit: malware that gives an attacker privileged access to an infected system, hides its presence or the presence of other software;
- Downloader or Dropper: malware designed to download or install additional malicious components.

Monappa K. A. points out [8] that classifying malware based on functionality is not always possible, because a single piece of malware may contain multiple functions that can fall into the many categories just mentioned. For example, malware may include a worm component that scans the network looking for vulnerable systems and may apply another malicious component such as a backdoor or ransomware virus when successfully exploited.

Malware can also be classified based on the attacker's motives. For example, if the malware is used to steal personal, commercial or proprietary information for profit, the malware may be classified as criminal software or commodity malware. If the malware targets a specific organisation or industry to steal information and gather intelligence for the purpose of espionage, then it may be classified as targeted or spyware [29].

Computer viruses are programs, just like a spreadsheet or a word processor. This distorted picture of computer viruses is the reason that the spectrum of responses to this topic range from sympathetic laughter to a knowing grin up to a panic over viral infection.

Factual explanations about these matters have generally been ignored up to now. There have been reports of “promiscuous disks,” of worms which eat through the computer, and “hard viruses which destroy the ROM.” To bring a little clarity to this confusion, this book is intended to be a guide in the world of computer viruses [15]. An interesting comparison between a biological virus and a computer virus is given.

J.Aycock in [12], proposes the following classification which includes: Logic Bomb, Trojan Horse, Back Door, Virus Worm, Rabbit, Spyware, Adware Hybrids, Droppers, and Blended Threats, Zombies.

Strictly speaking, the type of malware that replicates by attaching itself to other programs, but colloquially refers to malware in general. Usually contains a payload that performs unauthorized functions such as displaying messages, and deleting or modifying files [30].

The following table summarizes the results of a comparison of the two approaches - classical and modern - to describing threats.

Table 1. Comparison of approaches to describing threats

Criteria	Classical approach	Modern approach
Environment	Local executables, OS libraries	Cloud microservices, Docker containers/KBs
Implementation mechanisms	Disks (8", 5.25", 3.5"), physical access, email	Supply Chain Attacks (hacking through legitimate software updates)
Target	Malfunction, data corruption	Ransomware, hidden mining, AI model theft
Detection	Signature analysis, checksum verification	AI-powered behavioral analysis, Zero Trust architecture

Source: authors' elaboration

Note: The algorithms for implementing the SA remain logically identical to those described earlier, only the scale and technology stack change.

6. Mobile Threats

The evolution of mobile devices and threats have evolved almost in parallel. It should be noted that modern smartphones have a larger attack surface compared to conventional mobile phones. Attackers are mainly targeting Android and iPhone platforms [31].

Experts have adopted an approach that divides threats into three main types: device-level threats, network-level threats, and application-level threats.

Common mobile threats include malware, Trojans, spyware, ransomware, SMS/email phishing attacks and insecure networks.

An attacker can access the following data sets that are available on a typical smartphone:

- 1) Corporate and personal e-mails
- 2). Contacts (along with their e-mail and personal addresses)
- 3). Banking information
- 4). Instant Messaging logs
- 5). Pictures
- 6). Videos
- 7). Credit card Information
- 8). Location and GPS data
- 9). Health information
- 10). Calendar and schedule information.

Thus, mobile malware is on the rise, and attackers are shifting their efforts to smartphones and tablets, putting global mobile markets at risk. This trend is continuing.

7. Evolution of SA: from Computer Viruses to Service Models

Several stages in the development of SA should be distinguished.

Among them, the main ones are the following.

Stage 1: Experiments and games (1960s - early 1980s). The first computer abuses appeared in the early 1960s and were created to teach programming to students. During this period, programmers created malicious programmes and games such as 'The Colossal Cave Adventure' and 'Eliza'. These programmes were not dangerous and did not pose a threat to computer security.

Stage 2: Viruses (mid-1980s - late 1990s). After a certain period of time, the evolution of SAs has turned them into sophisticated mechanisms used to implement attacks on information objects, the purpose of which is to destroy information or disrupt digital services of various levels of criticality. Shadow markets offer a large set of products and services for the shadow digital economy, all of which are clearly criminal in nature. In the mid-1980s, the first computer virus, Brain, was created. During this period, many viruses were created that caused computers to crash and corrupt files. In response to this, anti-virus software emerged.

Stage 3: Internet worms (1990s-early 2000s). In the late 1990s, the first Internet worm, the Morris worm, appeared. This period was also characterised by the appearance of the first Trojans - malicious programs that hide inside official software and perform undeclared malicious functions without the user's knowledge.

Stage 4: Phishing and Spyware (2000s). The early 2000s saw the emergence of new types of abuse, such as phishing - attempts to obtain a user's personal information (such as passwords and credit card numbers) through fraud, and spyware - malicious software that spies on users and can intercept their personal data.

Stage 5: Spreading malware via social media (since the 2010s). With the rise of social media, a new opportunity to spread malware has emerged. Cybercriminals began to use social media to send spam, distribute phishing messages, and infect users' computers with malware. This period also saw the emergence of a new form of computer abuse - Ransomware (for blackmail and extortion).

SAs are the basis for the following types of attacks: active, passive, internal and external. An extended list of attacks includes the following: based on the use of social engineering methods, denial of service, malware attacks, and others. The following generalised list of attacks can be proposed, including: phishing attacks, DDoS, malware infection, supply chain attacks, man-in-the-middle attacks, targeted attacks (APT), Brute-Force, identity-based attacks (logins and passwords), password spraying, internal attacks, spoofing, attacks on IoT devices, social engineering, stealth attacks, botnet, routing, etc. [32].

At present, the developments and practical experience of using SA have led to the emergence of a set of models, the main drivers of the shadow digital economy, which have contributed to the transformation of complex attack mechanisms into an accessible 'boxed' product.

It should be assumed that it is possible to further develop the family of SA on the basis of modern IT components, primarily AI, machine learning, etc., in order to automate the work on their development. It is possible to predict the emergence of AI-agents oriented on the selection of goals, adaptation of the relevant tools, etc. All this may lead, in our opinion, to the emergence of a 'self-learning' system, and this, in turn, may lead to the construction of its own full-fledged infrastructure in the form of an autonomous ecosystem.

Cybersecurity experts are increasingly interested in AI-based systems. This helps to identify new opportunities and advantages over potential adversaries. However, it should be noted that new technologies (AI, machine learning, etc.) [33], [34], [35], need to be further tested and refined [36]. The created systems should demonstrate their stability and operability, but also prove safety in new situations, not to create fundamentally new problems, how soon it will be possible to solve these problems is still unknown.

In support of this, T. O'Reilly notes: "Artificial intelligence is now at a tipping point. We may be building engines of extraordinary performance, but we are not yet building the social mechanism that will make that performance broadly applicable and broadly useful. We just hope that they evolve in some way." [37].

Individual malware with the help of AI is transformed into service models that are used in the shadow digital economy [38], [39]. Let us cite the main ones, in their composition, first of all, the following:

- Cybercrime as a Service (CaaS), an umbrella model, provides the sale/rental of criminal digital tools and services through underground marketplaces;
- Ransomware as a Service (RaaS), this is a platform where Ransomware developers provide the tools and infrastructure and 'affiliates' perform the attacks;
- DDoS as a Service (DDoSaaS), this is the leasing of capacity for DDoS attacks;
- Phishing as a Service (PhaaS), these are turnkey phishing kits (templates, landings, automation);
- Malware as a Service (MaaS), this is the rental/sale of malware (loaders, stylers, RATs, etc.) and management infrastructure;
- Money Laundering as a Service (MLaaS), these are services/networks for 'cleaning' and moving criminal proceeds (intermediaries, mules, crypto-services);
- Vulnerability Research as a Service (VRaaS), these are 'contracted' vulnerability research/technology research (legal analogue - bug bounty; in the shadows - search for further exploitation/resale);

- Data as a Service (DaaS), this is the sale of stolen data sets: PII, customer databases, 'logs' of stylers, session cookies/tokens, etc.

We consider it necessary to note the importance of further research into the shadow digital economy in this direction. It should be noted that the work of the above models is based on high automation, decentralisation and transition to new service models of interaction. There is further development of technologies and management tools related to Agentic AI (to automate operations of information theft, generation of deepfakes, etc.), migration to encrypted messengers with preserving the balance between anonymity and convenience, transition to private blockchains to hide information about the sender, recipient and amount, use of crypto-mixers to mix cryptocurrencies of different users in order to break the connection between the original wallet and the destination address.

8. Conclusions

Malware undoubtedly has a negative technical, financial, social and emotional impact on systems and users. This is important to know because cyber security is seen as risk management and it is necessary to accurately assess how much damage a security breach can cause [12].

It is necessary to estimate the cost of malware incidents. We feel it is important to note that estimating the cost of malware is a very complex task. There are two types of costs to consider: real costs and hidden costs.

Real costs. The time that technical support staff spends troubleshooting affected computers can also be calculated. However, not all costs are so obvious.

Hidden costs. Hidden costs are costs whose impact cannot be accurately measured and may not even be known. Some businesses, such as banks and computer security companies, may suffer damage to their reputation due to a widely publicised malware incident. Regardless of the type of business, a leak of confidential information or customer data caused by malware can result in enormous damage to a company, no different than industrial espionage.

Thus, the main conclusion is the importance of malware research, the information about which is constantly being replenished in quantitative and qualitative terms. We should expect the emergence of new complex tools for counteraction.

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Digital Transformation of Moldova's Agri-Food Sector: Risks of Creating E-Commerce Platforms for Farm Products CRM

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Abstract. The digital transformation of Moldova's agricultural sector plays a crucial role in advancing national economic development by integrating producers into modern market dynamics, lowering transaction costs, and enhancing transparency across supply chains. Leveraging e-commerce platforms allows farmers to engage in direct sales to consumers and businesses, streamline logistics, broaden market access, and foster the growth of small and medium-sized enterprises. Digitalization also facilitates access to financial resources, encourages production upgrades, and contributes to the resilience and sustainability of rural communities. This paper explores both the benefits and the vulnerabilities associated with the digitalization of Moldova's agri-food sector. Particular attention is devoted to cyber threats — including data breaches, attacks on digital infrastructure, and forgery of electronic documents — as well as legal gaps such as insufficient regulation of online contracts, limited protection of digital signatures, and the absence of standardized approaches to product certification in virtual marketplaces. The socio-economic dimension is also addressed, focusing on risks of platform monopolization, limited digital literacy among farmers, and structural barriers to adopting online solutions. The article outlines general strategic directions for reducing these risks, emphasizing the importance of strengthening cybersecurity, refining the regulatory environment, improving farmers' digital competencies, and adopting transparent mechanisms for quality assurance. It argues that the successful digital transformation of agriculture requires an integrated approach that builds trust among market participants and ensures the long-term reliability of digital infrastructure.

Keywords. Digitalization, agricultural sector, e-commerce, cyber risks, legal regulation, online trade, Moldova.

1. Introduction

The Republic of Moldova has historically and traditionally been an agrarian country. For decades, agriculture shaped not only the economic landscape but also the nation's cultural code and the way of life for millions of people. The land has always been the main wealth, and working it - the foundation of existence.

However, today we are witnessing an alarming trend: the complete decline of the agricultural sector. Hundreds of thousands of hectares of land have been removed from cultivation, tens of thousands of farmers have gone bankrupt, and rural areas are rapidly depopulating. The share of agriculture in the country's economy is steadily declining, despite the fact that a fifth of all employed Moldovans still work the land, but with catastrophically low labor productivity.

The dynamics of the agro-sector's decline since 1990 are particularly disheartening. While in 1990 the share of agriculture in the economy was many times higher, today we observe a dramatic reduction of the sector. In the EU, over a similar period, the sector's share also decreased, but this decline was accompanied by a corresponding release of labor and an

increase in productivity. In Moldova, however, we see the preservation of archaic employment with minimal output.

Access to the internet, the basic tool of the digital economy, is available to only 74.1% of Moldovan households — 20 percentage points below the EU average of 94.1% [1, 2]. This means that a significant part of the rural population is cut off from the opportunities offered by the digital world.

Agriculture, as a strategic sector of the national economy, generates about 10% of the country's GDP. However, according to AmCham Moldova and MITP.md, the level of digital adoption in the agro-industry remains low: less than 25% of farms use digital tools for monitoring, planning, and sales, and the share of agricultural enterprises using digital sales channels does not exceed 10–12% [2]. At the same time, the IT sector accounts for 6.3% of GDP, demonstrating the potential for transferring successful digital practices to the agricultural sector.

According to the European Commission, more than 65% of Moldova's exports are directed to the European Union, where digital standards for agri-food chains are already implemented at a systemic level [3]. This makes the digitalization of Moldovan agriculture a necessary condition for increasing competitiveness in foreign markets and integrating into European digital supply chains.

In these critical conditions, digital technologies open a window of opportunity. The absence of a consistent state policy to protect local producers, combined with market openness to imports — often cheaper but not always of higher quality — has led to a systemic crisis.

A digital agri-platform operating on a direct-to-consumer (D2C) model can become the tool that allows local producers to survive and sell their products directly to consumers, bypassing the multi-level intermediaries who appropriate the lion's share of the profit. However, for this to happen, the state must create the conditions: ensure digital infrastructure, train farmers, protect platforms from cyber threats, and, most importantly, form the political will to protect the interests of its own local producers.

This paper examines existing e-commerce platforms in Moldova's agricultural sector, as well as European innovative projects that can serve as benchmarks. Special attention is paid to risk analysis — from cyber threats to market monopolization — and strategic directions are proposed for minimizing these risks within the context of national strategies and government programs.

2. Strategic framework: the Government's role in developing the agri-food sector

The foundation of all governmental initiatives in the field of agriculture and digitalization is the National Development Strategy "European Moldova 2030", approved by Law No. 315 of December 17, 2022 [4]. This document sets the development vector for the country, including the agri-food sector, in the context of European integration and the Sustainable Development Goals (SDGs).

Key provisions of the strategy relevant to the agricultural sector and digital platforms:

- ❖ Accelerated growth of labor productivity through attracting investments, technology and innovation transfer, and increasing competitiveness in the agri-food sector [5]. This creates a political mandate for investment in digital solutions, such as e-commerce platforms, which directly impact sales efficiency and farm productivity.
- ❖ Development of opportunities for innovation and entrepreneurship, improving the business environment, facilitating access to financing, and improving access to external

markets [5]. This justifies the need to create tools that help farmers enter markets, including through e-commerce support.

- ❖ Link to SDG 2.3: increasing agricultural productivity and incomes of small-scale producers through access to markets and financial services [6]. This is a direct indication of the need to support small farmers, who are the main beneficiaries of direct-to-consumer (D2C) platforms.
- ❖ Link to SDGs 8.2 and 8.3: stimulating productivity growth through technological modernization and supporting micro, small, and medium-sized enterprises [6]. This directly supports the idea of digital transformation of agribusiness and creating favorable conditions for digital startups in AgroTech.

It is important to note that the strategy does not contain direct mentions of "e-commerce platforms." However, it creates the necessary strategic framework within which such initiatives can and should develop, viewing them as a tool for achieving higher goals [7].

Specification in National Programs and Projects

Building on the "European Moldova 2030" strategy, sectoral documents are being developed, and specific governmental initiatives are being implemented. An analysis of the activities of the Ministry of Agriculture and Food Industry (MAIA) reveals a comprehensive approach to digitalizing the agricultural sector.

Table 1. Main directions of government activity [8]:

Direction	Specific Measures and Projects (2024–2025)	Significance for Agri-Platforms
Creating basic digital infrastructure	Development and implementation of information systems: Farmers' Register, RICA data collection network, Agricultural Machinery Register, AKIS system, E-ANSA	Create a transparent and verifiable database of producers, products, and supply chains. The AKIS system helps improve farmers' digital literacy
Institutional reform	Establishment of the Center for Agricultural and Consulting Advice, development of the concept for the AgroTek Park technology park	Form an ecosystem to support farmers, including digital skills training and innovation implementation
Harmonization with the EU	Participation in EU4Digital programs, preparation for IACS implementation, work on EU acquis chapters (11, 12, 13)	Orients national standards towards European ones, including traceability and quality requirements
SME and export support	ODA grant programs for digitalization and innovation (14.4 million lei for 34 companies, 21.2 million lei for 79 companies)	Direct support for companies wishing to adopt digital technologies and enter foreign markets

Food Security Strategy 2023–2030

The *Food Security Strategy 2023–2030* directly targets the structural problems of the sector. Data from the National Bureau of Statistics for 2022 shows a high level of self-sufficiency in fruits (205%) and grains (96%), but critical dependence on imports for meat

(78%), milk (63.5%), potatoes (69%), and vegetables (81%) [9]. The strategy provides for investments in milk processing, the construction of slaughterhouse infrastructure, and the creation of logistics centers for storing, sorting, and packaging vegetables and fruits [10]. E-commerce platforms can become a sales channel for local producers, helping them compete with imports and stabilize market supply.

However, declarations are not enough. Historical experience shows that without state support and protection, local producers cannot survive in an open market. This is an axiom confirmed by 30 years of post-Soviet experience. For the successful implementation of digital agri-platforms, the state must create the necessary conditions:

Table 2. Necessary conditions for the development of agri-platforms

Direction	Necessary Measures	Expected Result
Digital Infrastructure	Providing broadband internet to rural areas, supporting alternative communication technologies (LoRa)	Eliminating the digital divide, farmers' access to platforms
Digital Literacy	Creating rural innovation centers, farmer training programs, developing the AKIS system	Building human capacity for working on platforms
Legal Protection	Harmonizing legislation with EU norms, protecting producers' rights on platforms	Reducing legal risks, building trust in platforms
Cybersecurity	Developing national security standards for agri-platforms, certification	Protecting data and transactions
Financial Support	Grant programs for joining platforms, tax incentives, logistics subsidies	Lowering barriers for small producers
Institutional Support	Creating AgroTek Park, developing advisory services	Forming a support ecosystem

Source: developed by the author based on [8, 9, 10]

3. Analysis of existing agri-food platforms in Moldova and European innovative projects

The market for agri-platforms in Moldova is in an active stage of formation. Several key initiatives can be identified, differing in their business models and target audiences.

Table 3. Moldovan platforms: analysis of existing agri-food platforms

Platform / Launch Year	Type / Model / Main Focus	Key Features	Status / Dynamics
999.md 2015\ (agro-category created)	Largest national classifieds site (multi-vertical) with a special "Agriculture" section. All products, including agro (livestock, vegetables, fruits, milk, meat)	4.8 million visits/month 98% traffic from Moldova Free listings for farmers during the 2015 crisis 999Market project (partnership with the Ministry of Economy) Issues with illegal trade	Largest national platform, unique example of public-private partnership

Agromag.md 2023	B2B marketplace (multi-vendor). Agricultural inputs (seeds, fertilizers, machinery, equipment)	7,000 products 100 verified suppliers Integration with Agrobiznes.md portal	Record growth: 25K → 70K → 100K visitors (2023-2025)
Biofood.md 2022	B2C / B2B platform. Organic products	First organic platform in Moldova USAID/CNFA support MOVCA membership in IFOAM >100 products	Information on commercial success unavailable
Transoil Market 2022	B2B platform (direct purchasing). Grain crops (wheat, corn, sunflower)	Integration with TRANS OIL infrastructure (15 elevators, Giurgiulesti port) Direct sales without intermediaries Transparent real-time prices	Operational, integrated with an infrastructure giant
AgricolaHub.md 2022	Ecosystem / classifieds. Everything for agriculture + financial services	Integration with Maib (largest bank) Free listing Internal chat Information on grants, subsidies, loans	Operational, bank support ensures sustainability
Bondarenko Family 2024	Individual farm digitalization project. Own farm (cereals, orchards)	Weather station Website Remote field monitoring EU4Moldova support	Successful example, exports to the EU
Platform "Food security and food safety" 2020	Scientific-communication platform. Food security	Coordinator — Professor Rodica Sturza (ASM) Science-industry cooperation Online events (2020-2021 forum)	Operational, plays a scientific-coordination role
AgroMarket Hub 2025 (concept)	Concept (TUM project). Direct sales (D2C) for small farmers	QR traceability Shared logistics Seasonal food boxes 70% farmer willingness to participate	Only a concept, requires investment
MITP.md initiatives	Incubator / hub. Rural innovation hubs, agrotechnologies	Support for AgroTech startups Implementation of AI, automation, online marketing	Actively developing

The analysis of the platforms presented in the table reveals key features and trends in the formation of the Moldovan agri-platform market:

- **Diversity of models:** The Moldovan agri-platform market features various models — from classic B2B marketplaces (Agromag) to specialized purchasing platforms (Transoil Market), ecosystems with bank integration (AgricolaHub), and unique examples of public-private partnership (999.md with the 999Market project).
- **Dominance of 999.md:** In terms of scale and audience reach, 999.md has no equal — 4.8 million visits per month and 98% of traffic from Moldova make it the most important sales channel, including for agricultural products. The historic decision to provide free listings for farmers during the 2015 crisis demonstrates corporate social responsibility.
- **Successful niche projects:** Agromag.md shows impressive growth dynamics, indicating high demand for specialized B2B solutions in the agricultural sector.
- **Individual digitalization projects:** An example of successful digitalization of an individual farm is the family of Veronica and Veniamin Bondarenko from Slobozia village (Ștefan Vodă district) [15]. In 2024, with support from the EU4Moldova program, they received a grant for digitalization, which included installing a weather station, creating a website, and a digital platform for remote field monitoring.
- **Scientific support:** The Academy of Sciences platform plays an important coordinating role, linking science and practice, which is critical for innovation implementation.
- **Potential and gaps:** The AgroMarket Hub concept, developed at the Technical University, shows high farmer readiness for joint action (70%), but the lack of investment hinders its implementation [17].

European Innovative Projects in the Field of E-Agriculture

To understand the prospects and risks of developing e-commerce in Moldova's agri-food sector, it is useful to consider existing European projects that demonstrate advanced approaches to agricultural digitalization [18].

- 1) **Experimental Digital Platform LoRa in Agriculture:** The project aims to create a digital platform on an experimental farm using **narrowband radio communication (LoRa)** with internet access [18]. LoRa technology provides wireless communication with low power consumption and a long range, ideal for remote agricultural lands. For Moldova, where many rural regions face internet quality issues, LoRa could become an alternative solution for creating digital infrastructure.
- 2) **SOCLE Innovation AB:** This project disseminates innovative technologies among vegetable producers, providing **specific technical and economic indicators** adapted to the local production context [18]. Special emphasis is placed on resource conservation and maintaining soil organic matter. For Moldovan farmers, often distrustful of new technologies due to a lack of clear evidence of their effectiveness, this approach is critically important.
- 3) **Innovative Study of Robotic Mowing in Orchards:** The project tests autonomous (robotic) mowers for grass management in orchards [18]. For Moldova, with its developed horticulture (apples, plums, apricots, cherries), robotic mowing can reduce costs and decrease dependence on scarce seasonal labor.
- 4) **Vineyard 2.0:** A comprehensive project focused on three areas: plot monitoring and mapping (precision farming), semi-autonomous or assisted driving of machinery, and robotics in vineyards [18]. Given that viticulture and winemaking are strategic sectors

for Moldova, elements of this project could be integrated into e-commerce platforms to provide data on product origin and quality.

- 5) **European Research Initiatives:** The **D4AgEcol (Digitalisation for Agroecology)** project is funded by the EU to study the potential of digitalization as a factor contributing to the development of agroecological farming systems in Europe [19]. The **GreenFieldData** project, under the Marie Skłodowska-Curie Actions program, trains a new generation of researchers to address the challenges of the digital and green transition, developing IoRT-based solutions for sustainable agriculture [20].

Key Features of European Advanced Approaches

In summary, the main features of European advanced approaches to agricultural digitalization can be identified as follows:

- 1) **Technological diversity:** European projects cover a wide range of technologies — from simple communication systems for remote farms (LoRa) to complex robotic systems and artificial intelligence.
- 2) **Evidence-based approach:** Projects like SOCLE Innovation AB emphasize specific technical and economic indicators — exactly what Moldovan farmers need, as they often distrust technologies without clear evidence of effectiveness.
- 3) **Adaptation to local conditions:** A key principle of successful projects is adapting technologies to the local context (soils, climate, farm size), which is critically important for Moldova with its diverse conditions.
- 4) **Robotization of labor-intensive processes:** Projects on robotic mowing and autonomous driving show a way to solve the problem of labor shortages, which is particularly acute in Moldovan agriculture.
- 5) **Strategic sectors:** For Moldovan viticulture, the Vineyard 2.0 project provides a ready-made roadmap for digital transformation.
- 6) **Education and training:** The Hungarian experience of creating a Digital Agricultural Academy is directly applicable to solving the problem of low digital literacy among Moldovan farmers.
- 7) **Environmental sustainability:** Irish projects demonstrate how digital technologies can serve to preserve unique landscapes and biodiversity, which is also relevant for Moldova.

The reviewed European projects show that **the digital transformation of agriculture is not just about platforms for selling products, but also about deep technological modernization of production** [21]. For Moldova, this means that the development of e-commerce must go hand in hand with infrastructure development (LoRa), an evidence base for effectiveness (SOCLE), process automation, and enhanced traceability (Vineyard 2.0).

There is enormous potential for creating platforms for small and medium-sized producers. According to AmCham Moldova (2024), the share of agricultural enterprises using digital sales channels does not exceed 10–12% [2]. This means that the huge potential of digital sales remains unrealized.

E-commerce platforms can unite:

- small and medium-sized producers;
- farmers' cooperatives;
- returning migrants engaged in agricultural business.

Research conducted at the Technical University of Moldova shows that 70% of farmers are ready to participate in shared logistics, and almost half of consumers are willing to pay for delivery under the condition of verified product origin [17].

4. Step-by-step development of an E-Commerce platform (d2c) and risk analysis

Creating an e-commerce platform based on the D2C model for small and medium-sized agricultural producers and returning migrants requires a systematic approach. Based on an analysis of business processes and best practices, the following stages can be identified [3]:

The process of creating an e-commerce platform based on the D2C model for small and medium-sized agricultural producers includes six successive stages:

Stage 1. Situation analysis and goal setting:

- **determining the level of farm digitalization;**
- **analyzing the state of logistics infrastructure and user needs;**
- **formulating goals: increasing producer profitability, ensuring sales transparency, reducing the chain of intermediaries.**



Stage 2. Architecture development and technology selection:

- **designing a modular cloud system;**
- **integrating payment services (MAIB Pay, PayNet);**
- **developing a logistics module, analytical tools, and a user training system.**



Stage 3. Interface and content creation:

- **developing a multilingual interface (Romanian, Russian, English);**
- **adapting for mobile devices;**
- **creating and integrating training materials for farmers.**



Stage 4. Testing and training:

- **pilot launch with a limited number of users;**
- **conducting training webinars and workshops;**
- **identifying and fixing technical errors.**



Stage 5. Launch and promotion:

- **scaling the platform with support from MITP.md and AmCham.md;**
- **promotion through social media and regional agricultural associations.**



Stage 6. Monitoring and optimization:

- **analyzing performance indicators (sales volume, user satisfaction);**
- **regular feature updates;**
- **ensuring data protection and cybersecurity.**

Figure 1. **Step-by-step development of an e-commerce platform (D2C)**
(Source: developed by the author based on [3])

This approach will allow for the creation of a sustainable and secure digital ecosystem for agriculture, facilitating market expansion, increasing profitability, and integrating Moldovan farmers into international supply chains.

Successful platform implementation is impossible without a preliminary analysis of potential threats. The process of digital transformation in the agri-food sector, despite its obvious advantages, is associated with a number of risks and limitations requiring systematic analysis [22].

- ❖ **Technological risks.** The key challenge is the **low level of digital infrastructure in rural areas**. Access to broadband internet in rural Moldova remains limited, hindering the use of online platforms. Problems with software compatibility, failures in payment system integration, and insufficient reliability of cloud services can lead to data loss or platform malfunction [23].
- ❖ **Cyber and information risks.** As the volume of online transactions grows, so does the threat of **cyberattacks and leaks of confidential information** [24]. Farmer and trade platforms process data on customers, payments, and supply chains, making them targets for cybercriminals. The lack of systemic cybersecurity increases the likelihood of financial losses and loss of user trust.
- ❖ **Organizational and managerial risks.** Moldova's agricultural sector suffers from a **low level of digital literacy**, especially among small farmers and family farms. A comparative analysis shows that in Moldova, where the Agrarian University was closed in 2022, the situation with personnel training is worse than in EU countries [2]. Lack of skills in working with online platforms can lead to ineffective use of digital solutions.
- ❖ **Risks associated with seed and planting material trade.** Risks related to online seed trade deserve special attention. According to international experts, transactions between individuals (C2C) are difficult to track and are often conducted without phytosanitary certificates [25]. Material may come from small private productions without adequate disease and pest control. The likelihood of contamination of cultivated and wild plants through illegal supplies is extremely high, which could lead to economic and environmental damage.
- ❖ **Economic and market risks.** Creating and maintaining an electronic platform requires significant investment, which can be difficult for small and medium-sized producers. At the same time, high competition from foreign online markets may limit the opportunities of local participants. There is also a risk of platform monopolization by large players [26].
- ❖ **Legal and regulatory risks.** The lack of a clear regulatory framework for e-commerce in the agricultural sector also poses a threat. Moldova's e-commerce legislation is still not fully harmonized with European Union norms, creating difficulties for cross-border transactions and product certification [27].

The following measures must be implemented to neutralise the risks described:

- ❖ Development of digital infrastructure — national broadband programme.
- ❖ Improvement of digital literacy — rural innovation centres and training programmes.
- ❖ Harmonisation of legislation — acceleration of EU standards implementation.
- ❖ Strengthening cybersecurity — national standards for agricultural platforms.
- ❖ Support for small producers — grants, tax incentives, logistics subsidies.
- ❖ Ensuring traceability — QR code systems to confirm origin.
- ❖ Stimulating innovation — support for start-ups in the AgroTech sector.

5. Proposals and recommendations

Based on the analysis conducted, the following recommendations can be formulated to minimize the risks when creating e-commerce platforms in Moldova's agri-food sector.

- 1) **Development of Digital Infrastructure**-It is necessary to develop a national program to provide broadband internet to rural areas. Projects using LoRa technologies for remote farms, as shown in European examples, could be an alternative [18]. This also aligns with the Sustainable Development Goals (SDG 9) and the National Strategy "Moldova 2030" [4].
- 2) **Enhancing Digital Literacy**-The creation of rural innovation centers and training programs for farmers on working with digital platforms, CRM systems, and analytical tools is required. Programs should include not only technical skills but also the basics of cyber hygiene. The AKIS (Agricultural Knowledge and Innovation Systems) initiative, being developed by MAIA, is intended to address this task [8].
- 3) **Harmonization of Legislation**-It is necessary to accelerate the harmonization of national legislation with EU norms in the areas of e-commerce, data protection, and phytosanitary control. Particular attention should be paid to regulating C2C transactions with seeds and planting material, following the recommendations of the FAO Commission on Phytosanitary Measures [25]. Progress in this direction is demonstrated by MAIA's work on EU acquis chapters 11, 12, and 13 [8].
- 4) **Strengthening Cybersecurity** -The development and implementation of national cybersecurity standards for agri-platforms, including mandatory certification, data encryption, and personal data protection mechanisms. This must comply with the requirements of Law No. 48/2023 on cybersecurity [28].
- 5) **Creating Support Mechanisms for Small Producers** -Development of tax incentives and grant programs for small and medium-sized agricultural producers wishing to join digital platforms. The experience of Poland and the Baltic states shows that creating infrastructure for small exporters (consolidation centers, simplified customs procedures, special delivery tariffs) can significantly expand the export base [8].
- 6) **Ensuring Traceability and Transparency**-Implementing QR traceability systems to confirm product origin and quality will increase consumer trust and allow integration into European digital supply chains. The AgroMarket Hub study showed a high willingness of consumers to pay for delivery under the condition of verified product origin [17].
- 7) **Stimulating Innovation and Startups**-Supporting domestic startups in the agrotechnology sector, such as CityFarm, Greeno, and Solvi, which are creating new infrastructure solutions for farmers [29]. These companies are already demonstrating success internationally and could become drivers of digital transformation for the entire sector.
- 8) **Integration with Scientific Research** -Developing cooperation between agri-platforms and scientific institutions, such as the platforms of the Academy of Sciences of Moldova ("Food security and food safety"), to implement scientifically based approaches to digitalization [16].

6. Conclusion

The digitalization of Moldova's agri-food sector is not just a technological trend but a strategic necessity. In the long term, it can become an engine for sustainable economic growth, increasing export potential, and ensuring the country's food security.

The conducted analysis shows a comprehensive approach by the Republic of Moldova to this task. At the strategic level, the National Development Strategy "European Moldova 2030" sets goals for productivity, innovation, and support for small businesses. At the sectoral level, the Ministry of Agriculture and Food Industry is implementing specific measures to create basic digital infrastructure (Farmers' Register, RICA, E-ANSA), provide institutional support (AgroTek Park, consulting centers), and harmonize with European standards [8].

Analysis of existing platforms shows that a certain landscape of agri-platforms has already formed in Moldova — from successful B2B marketplaces (Agromag.md) to specialized niche projects (Biofood.md) and platforms integrated with large businesses (Transoil Market, AgricolaHub.md). A unique role is played by 999.md, whose historic decision to provide free listings for farmers during the 2015 crisis and partnership with the Ministry of Economy in the 999Market project demonstrate the potential of public-private cooperation in supporting local producers.

European innovative projects (LoRa, SOCLE, Vineyard 2.0) set benchmarks for further development, showing that the digital transformation of agriculture is not only about platforms for selling products but also about deep technological modernization of production [18].

However, the digitalization process is fraught with serious risks: technological (weak infrastructure), cybernetic (data leaks), organizational (low digital literacy), legal (incomplete harmonization with EU norms), and economic (risk of monopolization). It is important to note that the infrastructure being created by the state is designed to minimize these risks — ensuring the reliability of data on producers, improving digital skills, and creating favorable conditions for exports.

Successful digital transformation requires an integrated approach that fosters trust among market participants and ensures the long-term reliability of digital infrastructure. It is necessary to:

- strengthen cybersecurity;
- improve the regulatory framework;
- enhance the digital competence of farmers;
- implement transparent quality assurance mechanisms.

For Moldova, where agriculture has historically been the foundation of the economy and identity, digital transformation opens a window of opportunity. As the experience of the Bondarenko family from Slobozia shows, investment in digital technologies is not just modernization, but an expression of faith in the potential of the native land and the creation of a sustainable future for the next generations [15].

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E-Commerce: Innovative Tools for Digitalizing Trade in Moldova

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Abstract. Global digitalization has transformed online commerce into a key factor for economic development. For the Republic of Moldova, this shift is a powerful opportunity to open up new markets, boost entrepreneurship, and connect local producers to global supply chains. This article takes a close look at the innovative tools driving modern e-commerce, from online marketplaces and digital payment systems to automated logistics and smart marketing tech. We explore how these tools are making transactions more transparent, cutting costs, and speeding up buying and selling. A special focus is placed on the impact for small and medium-sized businesses. The analysis also addresses the hurdles that slow down digital adoption in Moldovan trade, such as gaps in infrastructure and digital skills. The piece argues that for Moldova to truly succeed in digitizing its trade sector, a well-rounded strategy is essential. This includes modernizing regulations, strengthening cybersecurity, and creating strong support programs for entrepreneurs. In conclusion, there is a clear need for more research and the active adoption of innovative practices to fast-track the Moldovan economy's integration into the global digital marketplace.

Keywords: e-commerce, innovation, digitalization of trade, Moldova, online platforms, digital payments, logistics.

1. Introduction

Global digitalization has transformed online commerce into a key factor for economic development. For the Republic of Moldova, as for many countries with transition economies, this transformation opens up powerful opportunities: access to new markets, stimulation of entrepreneurship, and integration of local producers into global value chains. At the same time, the process of digital adaptation faces serious challenges, including infrastructure constraints, a digital skills deficit, and the need to harmonize legislation with the norms of the European Union (EU). The course towards European integration, adopted by Moldova, gives this issue particular urgency, requiring not only technological but also regulatory modernization of the e-commerce sector. However, digitalization brings not only benefits but also significant environmental costs, making the search for pathways to a sustainable digital economy an imperative.

From the first experiments with Electronic Data Interchange (EDI) in the 1960s to giants like Amazon and Alibaba, e-commerce has come a long way. Today, it is not just a sales channel but a complex ecosystem operating in a VUCA world (Volatility, Uncertainty, Complexity, Ambiguity). This reality, characterized by volatility, uncertainty, complexity, and ambiguity, exerts colossal pressure on business. The response to this challenge is digital transformation, whose goal is not just technology implementation but value creation. The main value and core digital reality becomes Customer Experience. Competition revolves around

creating a seamless, personalized, and contextual customer journey from the first touchpoint to after-sales service.

There is a gap between the rapid development of business practices in e-commerce and the academic understanding of these processes. Small and medium-sized enterprises (SMEs) face the greatest difficulties trying to adapt to the dual transition — simultaneous digitalization and the shift towards sustainable development. The purpose of this article is to synthesize existing knowledge and present a comprehensive picture of the role of innovation in e-commerce. This includes a classification of innovation types, an analysis of the impact of key disruptive technologies, their connection to sustainable development, and ultimately, a proposal for a practical framework for implementing innovations in SMEs, based on the foundational work of Purcarea (2024).

Objective of the Study. The aim of this article is a comprehensive analysis of the role of innovation in the transformation of electronic commerce in Moldova, examining their evolution from a technological driver to a tool for sustainable development. The work sets the following tasks: (1) to present a review and analysis of scientific publications on the topic of innovation in e-commerce; (2) to define the main concepts and develop a typology of digital trade; (3) to structure and analyze the key innovations applied in the Moldovan e-commerce sector; (4) to assess the alignment of this development with the UN Sustainable Development Goals (SDGs) in the context of European integration; (5) to propose a practical system for evaluating innovations to choose the optimal strategy.

2. Theoretical Foundations: Innovation as the Engine of the Fourth Industrial Revolution

From Industry 4.0 to Industry 5.0 and the Business2Robot2Consumer (B2R2C) Concept

The concept of the Fourth Industrial Revolution (4IR), initiated in Germany as "Industry 4.0," describes the shift caused by the fusion of digital, physical, and biological worlds. It signifies the digital transformation of industry based on cyber-physical systems, the Internet of Things (IoT), and cloud computing. However, today we are already talking about Industry 5.0, which expands this focus. It prioritizes not only efficiency but also sustainability, human-centricity, and resilience (the ability to withstand and quickly recover from shocks). Industry 5.0 is intended to lead both the digital and "green" transitions, ensuring prosperity within planetary boundaries.

In this context, robotization is having an increasing impact on e-commerce. From warehouse automation to drones for the "last mile," robots are becoming an integral part of the value chain. This gives rise to a new concept — **Business2Robot2Consumer (B2R2C)**. Marketers and strategists need to consider that their target audience is increasingly not only people but also algorithms, smart speakers, and robot assistants that make purchases on behalf of a person or on their behalf.

Digital Disruption and Business Model Transformation

Digital disruption occurs when new players with innovative business models challenge established "incumbents." According to Clayton Christensen's theory of disruptive innovation, new competitors often enter the market with simpler and cheaper solutions, targeting overlooked or underserved segments. They use a disruptive innovation strategy, while incumbents focus on sustaining innovations, improving products for their most demanding customers, and often miss the threat from below.

Key to understanding digital business is the "iron triangle," describing three interconnected perspectives of any digital model:

- **Who? (participants):** creating and exchanging value in the network.
 - **What forms? (value):** how value is specifically created and delivered.
 - **Sustainability? (durability):** how the model maintains competitiveness over time.
- Achieving a balance between these three elements is the main strategic task for any company in the era of digital disruption

3. Classification and Role of Innovations in E-commerce

Understanding the multifaceted nature of innovation is key to analyzing the transformation of e-commerce. Based on the comprehensive study by Faccia et al. (2023), AmCham (2024), Vasilache A. (2004). which provides a foundational typology for understanding technological change, we can identify and analyze various types of innovations, each playing a unique role in the digitalization of trade, possessing its own advantages, and carrying certain risks.

1). Disruptive Innovations

- **Role and Impact:** Disruptive innovations do not just improve the existing — they create new markets and value networks, often starting with simple and affordable solutions in niches ignored by established players. In e-commerce, their role is fundamental: they democratize market access for both sellers and buyers.
- **Pros:** Creation of entirely new business models (e.g., marketplaces uniting millions of sellers and buyers). Stimulation of competition and price reduction for the end consumer. Expansion of consumer choice and reach to a global level.
- **Cons / Risks:** High degree of uncertainty and risk of failure. Destabilization of established markets, potentially leading to the bankruptcy of traditional players and job loss. Require significant changes in legislation and regulation.
- **Examples:** The emergence of giants like Amazon and Alibaba completely changed the retail landscape. A more local example for Moldova is the launch of the 999.md/ro/marketplace, which, although still in its initial stage of development, is already creating a new ecosystem for local sellers and buyers, competing with traditional sales channels.

2). Sustaining Innovations

- **Role and Impact:** This is the main driver for the continuous improvement of existing products and services. They aim to meet the needs of current customers, making products better, faster, more convenient, and more reliable. In digital trade, this is the engine for improving the quality of customer experience.
- **Pros:** Predictability and relatively low risk. Allow companies to retain and strengthen their market share. Increase customer loyalty through continuous improvement of familiar services.
- **Cons / Risks:** A focus on sustaining innovations can lead a company to miss the emergence of disruptive technologies and new market niches (the "incumbent's trap"). They do not create new markets, only develop existing ones.
- **Examples:** Implementing faster delivery (e.g., expanding the geography and speed of courier services like Nova Poshta in Moldova), improving the interface of an online store for easier navigation, optimizing the mobile version of the site, implementing loyalty programs.

3). Breakthrough Innovations

- **Role and Impact:** These are innovations that create new technological trajectories and often lie at the intersection of different fields. They do not just improve but

fundamentally change the way a need is met, making possible what was previously impossible

- **Pros:** Ability to create entirely new product and service categories. Give the companies that first implement them a huge competitive advantage. Can dramatically increase efficiency and reduce costs.
- **Cons / Risks:** High development cost and complexity. Require significant changes in behavior and skills from companies and consumers. Often face infrastructure unreadiness or regulatory barriers.
- **Examples:** Creation of digital wallets and instant payment systems (like the new MIA system in Moldova), platform solutions uniting vast ecosystems (Amazon Web Services as a platform for thousands of other businesses)

4). Frontier Innovations

- **Role and Impact:** These are innovations at the cutting edge of scientific and technological progress. They are at the stage of experiments and research, and their potential is yet to be revealed. For digital trade, they define the contours of the future.
- **Pros:** Potential for radical efficiency gains (e.g., autonomous drone delivery), personalization (AI), transparency (blockchain). Open access to new, previously non-existent data and analysis opportunities.
- **Cons / Risks:** Extremely high degree of uncertainty and investment risk. Technologies may prove commercially unviable or face insurmountable ethical or regulatory obstacles. Require unique competencies.
- **Examples:** Using the Internet of Things (IoT) to create fully automated supply chains, applying 5G for augmented reality (AR) technologies in shopping, experimenting with quantum computing to optimize logistics.

5). Radical Innovations

- **Role and Impact:** Unlike breakthrough innovations, radical innovations create entirely new products for the *existing* market. They replace old technologies, completely supplanting them.
- **Pros:** Allow a company to achieve a dominant market position if it can quickly capture share by displacing old products. Stimulate technological progress in the industry.
- **Cons / Risks:** High risk of market rejection if the new product is too complex or does not solve real consumer problems. Require significant investment in marketing and consumer education.
- **Examples:** The shift from traditional retail to online marketplaces, the emergence of VR stores as a new form of brand interaction, the rise of social commerce through Instagram and Facebook, which created a new sales channel for millions of small entrepreneurs.

6). Architectural Innovations

- **Role and Impact:** They restructure the internal architecture of a system, leaving its components unchanged. This is a change in how the parts of the system interact with each other. In digital trade, this is the foundation for flexibility and scalability.
- **Pros:** Allow quick adaptation to changing market demands. Simplify the integration of new technologies and services. Increase system stability and reliability.
- **Cons / Risks:** Complexity and high cost of restructuring established architectures. Require a highly qualified development team. May temporarily reduce system performance during the transition period.

- **Examples:** Transitioning from a monolithic platform to a microservices architecture, allowing individual parts of an online store to be updated and scaled independently. Implementing a headless CMS, which separates content management from its presentation, allowing the same content to be used on the website, mobile app, and social networks.

7). Modular Innovations

- **Role and Impact:** They affect individual system components, replacing them with new, more advanced ones, but leaving the overall architecture unchanged. This is a way of gradual but deep modernization.
- **Pros:** Lower risk and cost compared to architectural changes. Allow quick implementation of new functions by replacing an "old module with a new one." Simplify system maintenance and updates.
- **Cons / Risks:** Potential compatibility issues of the new module with the old ones. Risk of vendor lock-in if the module is too tightly integrated with a single supplier.
- **Examples:** Replacing an old payment gateway with a new, more functional and secure one via API. Implementing a new AI-based product recommendation system without changing the rest of the store's functionality.

8). Incremental Innovations

- **Role and Impact:** This is a continuous stream of small, gradual improvements. They form the basis of daily work on optimizing products and processes. Their cumulative effect over time can be enormous
- **Pros:** Low risk and cost. Easy to test and implement. Allow continuous learning from user feedback and data. Create a culture of continuous improvement.
- **Cons / Risks:** Individually, each innovation has a small effect. Can create an illusion of development when a company misses the need for more fundamental, radical changes.
- **Examples:** Regular A/B testing of headlines and buttons on a website to increase conversion. Continuous optimization of product description texts based on search queries. Minor improvements to the checkout interface to reduce shopping cart abandonment.

9). Open vs. Closed Innovations

- **Role and Impact:** These two paradigms define the *source* of innovation. Open innovation involves the active use of external ideas, partnerships, and technologies. Closed innovation relies on internal research and development to protect intellectual property.
- **Pros (Open):** Access to a wider pool of ideas and talent. Accelerated development by using ready-made solutions. Reduced R&D costs. Creation of ecosystems and network effects.
- **Cons (Open):** Risk of losing control over key technologies. Complexity of managing intellectual property rights. Dependence on external partners.
- **Pros (Closed):** Full control and protection of unique developments. Possibility of creating a sustainable long-term competitive advantage.
- **Cons (Closed):** High costs and risks of internal R&D. Limitations of own expertise and perspective. Risk of "reinventing the wheel" and lagging behind the market.
- **Examples (Open):** Using Shopify to quickly create an online store, integrating payment services like PayPal or local PSPs, participating in partner programs and hackathons.

- **Examples (Closed):** Developing a proprietary e-commerce platform with unique functionality, creating a unique recommendation algorithm that the company does not disclose to competitors.

The detailed classification of innovations carried out is not just an academic exercise. It is a powerful analytical tool that provides businesses, regulators, and researchers with several important advantages.

What does this knowledge give us?

- **Strategic Planning and Positioning:** Understanding the different types of innovations allows a company to clearly define its strategy. Will it be a "pioneer" implementing frontier technologies (high risk, high potential reward), or a "fast follower" improving existing solutions (incremental/sustaining innovations) with lower risk? This knowledge helps answer the question: "Who are we in this market and where do we want to go?"
- **Resource Optimization and Risk Management:** Each type of innovation requires different resources and carries different risks. Understanding this allows for more efficient allocation of R&D budgets and investments. A company can balance its innovation portfolio, investing simultaneously in "risky but promising" breakthrough projects and in "reliable but evolutionary" sustaining improvements.
- **Competitive Analysis:** Using this typology as a "map," one can analyze the actions of competitors. What type of innovation is your main rival using? Are they building an ecosystem (disruptive) or just improving their website (sustaining)? This allows anticipating their next steps and developing an effective response.
- **Assessing Market and Ecosystem Maturity:** At the country or region level (as in the case of Moldova), this classification helps assess the maturity of the digital ecosystem. The predominance of incremental innovations may indicate stagnation and a lack of breakthrough ideas. Conversely, the emergence of even isolated disruptive or architectural projects (like the launch of the 999.md marketplace or the introduction of the national MIA instant payment system) is a strong signal of the market transitioning to a new level (AmCham, 2024).

How to evaluate which type of innovation is "better"?

There is no universal answer to this question. The "best" innovation is the one that best aligns with the company's current goals, resources, and context. For an objective assessment, we propose using a multi-criteria approach, considering innovations not as isolated phenomena, but as elements of a single portfolio.

How to use this table?

- **Define your goal.** What is more important for you: quickly capturing market share with minimal risk (focus on incremental/sustaining innovations) or creating a new market with potential for super-profits, but also high risk (focus on disruptive/breakthrough)?
- **Assess your resources.** Do you have the capital for long-term research (frontier innovations) and is your team ready for high uncertainty? Or is the budget limited and quick returns needed (incremental)?
- **Analyze the context.** Is your market mature? How intense is the competition? What are your customers' expectations?
- **Aim for balance.** The most sustainable strategy is not betting on one type of innovation, but creating a balanced portfolio. For example: 70% of resources on sustaining and incremental innovations (provide current income and loyalty), 20% on architectural and breakthrough (prepare the company for tomorrow), and 10% on disruptive and frontier experiments (seek opportunities for the day after tomorrow).

Table 1. Comparative analysis of innovation types for choosing the optimal strategy

Evaluation Criterion / Innovation Type	Disruptive	Sustaining	Breakthrough	Frontier	Architectural	Incremental
Market Growth Potential	Extremely High (creating new markets)	Low / Medium (improving share in existing market)	Very High (capturing new niches)	Uncertain, potentially revolutionary	High (improving efficiency and flexibility)	Low
Risk Level	Very High	Low	High	Critically High	Medium	Very Low
Required Investment	High	Low / Medium	Very High	Extremely High	High	Low
Time to Result	Long-term	Short-term	Medium / Long-term	Long-term (experiments)	Medium-term	Short-term
Impact on Customer Experience (CX)	Revolutionary (new experience)	Evolutionary (improving current experience)	Radical change in experience	Creation of fundamentally new experience	Indirect (via speed and reliability)	Small, but continuous improvement
Impact on Operational Efficiency	High (new business models)	Medium (process optimization)	High	Potentially very high	Very High (system flexibility)	Low
Applicability for Moldova (example)	999.md/ marketplace (creating local C2C/B2C market)	Improving interface and delivery speed at emag.ro , darwin.md	MIA instant payment system	Pilot projects for delivery drones (in perspective)	Banks transitioning to microservices architecture for their apps	A/B testing of landing pages

Knowing the typology of innovations and being able to evaluate them against key criteria transforms the innovation process from a chaotic search for "something new" into a manageable strategic discipline. For Moldova, on the threshold of active European integration, this approach allows not only copying best global practices but also creating its own unique competitive advantages, optimally using limited resources and adapting to the specifics of the local market.

4. Innovations in Moldova's E-commerce: Structure and Dynamics

The Moldovan e-commerce market, according to the detailed report by AmCham Moldova (2024), shows steady, though uneven, growth.

Table 2. Key indicators of the Moldovan e-commerce market (2023)

Indicator	Value (2023)	Notes
Total market volume (goods + services)	EUR 358.6 million	Growth of 15.2% compared to 2022
Goods market (B2C goods)	EUR 229.1 million	63.9% of the market, growth of 18.8%
Services market (B2C services)	EUR 129.5 million	36.1% of the market, growth of 9.4%
E-commerce share in retail trade	5.60%	Indicates significant growth potential
Number of active e-shops (goods)	470-520	Estimate based on analysis of 420 stores
Number of active online platforms (services)	~480	Platforms accepting online payments
Active online audience (18-65 years, urban)	~327,600 people	~20% of the adult population
Average monthly e-commerce spending	EUR 91.4	Including EUR 58.4 on goods

[Source: AmCham, 2024]

The analysis of the Moldovan e-commerce market conducted by AmCham Moldova (2024) identified four key groups of innovations that have become growth drivers for the sector. By the beginning of 2026, these directions not only maintained their relevance but also received significant development.

1. Development of e-hypermarkets and the ecosystem approach

Projects like Smart, PandaShop, and Smadshop laid the foundation for the formation of a mature online retail market. By early 2026, these platforms evolved from simple online stores to full-fledged ecosystems. For example, **Pandashop.md** is actively developing its mobile application, offering not only an expanded assortment (from electronics to home goods, auto accessories, and office supplies) but also integrated solutions: convenient payment methods (including online, cash on delivery, bank transfer), fast delivery throughout Moldova, and a personalized approach to customers.

The **999.md marketplace**, in turn, continues to strengthen its position, offering goods unique to the Moldovan market, including international brands (e.g., IKEA furniture through local partners), which creates a competitive advantage over traditional offline retail and expands consumer choice .

2. Food delivery services (q-commerce) and hyper-personalization

The Straus and Glovo projects, launched during the pandemic, had by 2026 become an integral part of the daily lives of Moldovan consumers, radically changing consumption habits in the ready-meal segment. The **Straus.md** service, by early 2026, had significantly expanded its presence, uniting around 180 establishments with diverse cuisines — from classic burgers and pizza to Mexican, Thai, Indian, and traditional Moldovan cuisine. Key innovations included:

- Personalized recommendations based on order history.
- Process transparency: the ability to track order status in real-time, rate restaurants, and leave comments on the composition of dishes.
- Technical excellence: regular application updates aimed at increasing loading speed and operational stability, as well as bug fixes.

3. Development of "last mile" logistics

The expansion of operators like **Fan Courier** and **Nova Poshta** continues to play a critical role in the development of e-commerce. By 2026, their coverage networks became even denser, covering not only large cities but also remote settlements. Competition among logistics operators led to:

- Reduced delivery costs for end consumers and retailers.
- Shortened delivery times (emergence of express delivery services on the day of order).
- Development of a network of parcel lockers and pickup points, increasing convenience for buyers who can collect goods at any convenient time.

5. Security Evolution: From 3-D Secure Implementation to Dynamic Authentication and European Standards

If in the early 2000s, the implementation of the **3-D Secure** protocol (Verified by Visa, Mastercard SecureCode) by Moldovan banks and the Romcard processing center was a fundamental innovation that laid the foundation for secure online payments (Vasilache, 2004), then by 2026 this system has evolved to a qualitatively new level.

Key changes by 2026 include:

- **Transition to dynamic authentication (3D Secure 2.0).** The static password, vulnerable to phishing, has given way to dynamic one-time passwords (OTP). Moldova Agroindbank (MAIB) was the first in Moldova to implement this standard, making the use of stolen card data online practically impossible (Turcan A., 2024b).
- **Expansion of authentication methods.** Modern 3DS implies multi-factor authentication: confirming purchases via biometrics (Touch ID / Face ID) in banking mobile apps, push notifications, and frictionless authentication, where the system analyzes over 100 transaction parameters and confirms the payment in the background without bothering the user (Vasilache, 2004).
- **Harmonization with European regulatory standards.** By 2026, the Moldovan financial sector is integrating into the European regulatory field:
 - The implementation of Strong Customer Authentication (SCA) requirements (analogous to the European PSD2 directive) makes strong authentication mandatory for the vast majority of online payments. Transactions without 3DS verification may be declined by banks for security reasons (Turcan A., 2024a).
 - The National Bank of Moldova (NBM) is actively implementing the European Digital Operational Resilience Act (DORA), which establishes uniform

requirements for ICT risk management and digital resilience testing for all financial organizations (Turcan A., 2024a).

- **Mandatory standard for successful transactions.** By 2026, 3DS support has become not just a "feature," but a necessary condition for a high level of payment conversion. Many banks may "soft decline" transactions from cards not ready for 3DS, stimulating all market participants to adopt modern standards (Vasilache, 2004).

Thus, if the initial implementation of 3-D Secure was the foundation of trust, then by 2026 we are witnessing the formation of a **holistic, multi-level security ecosystem**, based on dynamic authentication, biometrics, strict regulatory requirements (SCA, DORA), and harmonization with European standards.

At the same time, the Moldovan market retains a number of specific features. The main one is the dominance of cash or card on delivery, which is associated with a relatively low level of consumer trust. This practice entails additional operating costs for e-retailers (AmCham, 2024).

- **Innovations as a Catalyst for Sustainable Development**

The Dual Transition: Synergy of Digitalization and Sustainability

Sustainable development is the path, and sustainability is the ultimate goal, requiring a balance of economic, social, and environmental factors. Digitalization, in turn, offers many tools to achieve this goal.

The dual transition means that companies must simultaneously manage digital transformation and the integration of ESG (Environmental, Social, Governance) principles into their operations. Supply chain responsibility becomes critically important: consumers and regulators demand transparency in the origin of goods, ethical production, and minimization of the environmental footprint — a challenge highlighted in global discussions on digital sustainability.

The development of e-commerce directly correlates with the achievement of several UN Sustainable Development Goals, as outlined in key international reports (UNCTAD, 2024):

- **SDG 8 – Decent Work and Economic Growth:** Creation of new jobs in the digital sector, support for SMEs through access to online markets — *Package of Measures for De-bureaucratization, Approved in December 2025 [cited in Moldpres, 2026];
- **SDG 9 – Industry, Innovation, and Infrastructure:** Development of digital and logistics infrastructure, introduction of innovations in trade processes — *Government Decision on the Digital Transformation Program for the Energy Sector for 2026–2030 [Approved in October 2025]*;
- **SDG 4 – Quality Education:** Digital transformation of education is critically important for training qualified personnel capable of working in the new digital reality and safely using its capabilities — *Digital Transformation Strategy of the Republic of Moldova for 2023–2030 (Draft)*.
- **SDG 10 – Reduced Inequalities:** Digital transformation strategies should aim to reduce the digital divide between urban and rural residents, ensuring equal access to services and opportunities — *National Development Strategy "European Moldova" 2030*;

The Environmental Footprint of Breakthrough Technologies and the Path to Sustainability

The relationship between digitalization and environmental sustainability is complex and multifaceted. Global research emphasizes that digitalization has a significant environmental footprint throughout the entire technology life cycle: from raw material extraction to the disposal of electronic waste. This makes the search for pathways to a sustainable digital economy an imperative (UNCTAD, 2024).

Impact of key breakthrough technologies on sustainable development:

- **Artificial Intelligence (AI) and Machine Learning (ML):** They permeate all aspects of e-commerce. AI enables personalized recommendations, optimizes real-time pricing, forecasts demand for inventory management, and automates customer support with chatbots. However, AI requires significant computing power, leading to increased energy and water consumption in data centers — a growing concern addressed in international sustainability frameworks.
- **Immersive Reality Technologies (AR/VR/XR):** They blur the line between online and offline. AR fitting rooms allow you to "try on" clothes or see how furniture would look in a room. Virtual showrooms create a new level of engagement, transforming e-commerce into iCommerce (immersive commerce).
- **Web3 Technologies (Blockchain, NFT, smart contracts):** They offer a decentralized approach, increasing transparency and trust. Blockchain can be used to track the authenticity of goods (luxury, art), and smart contracts for automating payments and managing supply chains. New NFT-based loyalty models can create deeper connections with customers. However, cryptocurrency mining is an extremely energy-intensive process, a fact well-documented in analyses of digitalization's environmental impact.
- **Generative AI (GenAI):** Became a real breakthrough in 2023. Tools like ChatGPT and DALL-E are revolutionizing content creation. They allow instant generation of thousands of unique product descriptions, creation of visuals for marketing campaigns, development of new product designs, and provision of personalized real-time customer support (Faccia et al., 2023).

Innovations in the following areas are necessary for the transition to sustainable development:

- **Logistics and the "last mile":** Optimizing delivery routes, using electric vehicles and bicycles, pickup points (click&collect) instead of courier delivery for every single order (AmCham, 2024).
- **Packaging:** Switching to recyclable and biodegradable materials, optimizing packaging size, eliminating excess plastic (AmCham, 2024).
- **Circular economy (economie circulară):** Marketplaces can become drivers of the circular economy, actively promoting the sale of used, refurbished goods and creating platforms for buybacks — a key recommendation for aligning digital growth with sustainability goals (UNCTAD, 2024).
- **Integrating sustainability into the business model:** Successful companies no longer view sustainability as a separate PR campaign. They integrate it into the core of their strategy. For analyzing readiness to adopt such innovations, theoretical frameworks like TAM (perceived usefulness and ease of use), TPB (influence of social norms and perceived control), and TOE (technological, organizational, and environmental context) are used.

6. Practical Guide: From Theory to Action for Small and Medium Enterprises (SMEs)

Based on the synthesis of theoretical knowledge and empirical data, an authorial tool was developed by Purcarea (2024) — the **"Decision Pyramid for Using Breakthrough Technologies by SMEs in E-commerce"**. It consists of six sequential levels (P1-P6).

- **P1: Combining Digital Transformation with Sustainable Development.** Foundational level. The SME must clearly define how it combines digital initiatives with sustainable development goals, assess its environmental footprint, and choose the right approach to transformation (for a new or already operating business). This also requires alignment with national strategies, such as the Draft Digital Transformation Strategy of the Republic of Moldova for 2023-2030.
- **P2: Fundamental Choice of E-commerce Architecture.** A critical decision affecting scalability and flexibility. This involves choosing between monolithic architecture, microservices, or headless solutions, and correctly selecting tools for back-end, front-end, checkout, and marketplace functionality, based on principles outlined by Vasilache (2004).
- **P3: Developing the Capacity for Technological Transformation.** This involves assessing the current IT infrastructure, defining user profiles, implementing flexible methodologies (Agile/DevOps), and ensuring cybersecurity. Understanding how specific technologies (AI, IoT, Blockchain) can be applied to increase productivity is essential for modern e-commerce businesses — a key insight from global digital economy analyses.
- **P4: Understanding Customer Motivations for Adopting New Technologies.** An in-depth study of the target audience is necessary: what is more important to them — convenience, personalization, innovativeness, price, or social responsibility? This also includes developing educational materials for customers (tutorials, knowledge bases), based on insights from the Moldovan market (AmCham, 2024).
- **P5: Using Generative AI.** This level focuses on the most current trend. Implementing GenAI for automating content creation (descriptions, design), improving customer service (smart chatbots), personalization, and assortment management across all channels (e-commerce, m-commerce, social, voice) represents a significant opportunity for SMEs to enhance their competitiveness (Faccia et al., 2023).
- **P6: Customer Centricity and Continuous Experience Improvement.** The pinnacle of the pyramid. This involves using all previous levels to create a seamless, personalized, and immersive customer experience. Continuous collection of feedback and data analysis for improvement directly leads to increased loyalty and profitability, a key finding in both theoretical frameworks and the Moldovan market analysis (AmCham, 2024).

7. Conclusion

The conducted analysis allows drawing several key conclusions. Innovations in modern e-commerce are not just about implementing individual technologies, but a comprehensive transformation of the business model, corporate culture, and operational processes. Success in the new VUCA reality requires companies, especially SMEs, to simultaneously manage digital transformation and the shift towards sustainable development. Customer experience, enriched by immersive technologies and AI-based personalization, becomes the central element of competitiveness.

For Moldova, the path to sustainable development of digital trade is inextricably linked with European integration. The legal and strategic framework being created by the country in close cooperation with the EU provides a solid foundation for this development. Harmonization with European norms not only facilitates cross-border operations for businesses and citizens but also ensures a high level of consumer protection, stimulates investment and innovation. However, the success of this path depends on the ability of the state and businesses to jointly manage the risks associated with cybersecurity and rapid technological changes, as well as on investments in human capital and digital education (Turcan A., 2024a, 2024b).

The proposed "Decision Pyramid" developed by Purcarea (2024) represents a practical tool that will help small and medium-sized enterprises structure this complex path and effectively use breakthrough technologies to enhance their competitiveness.

This work opens up several perspectives for further research. Firstly, an in-depth study of the long-term impact of generative AI on all aspects of e-commerce — from value creation to ethical dilemmas - is needed. Secondly, the development of universal and accurate methodologies for measuring the environmental and social footprint of digital commerce is an urgent issue, which would allow assessing real progress towards sustainable development — a challenge recognized in international policy discussions. Thirdly, the adaptation strategy of small and medium-sized businesses to the rapidly changing technological landscape, especially under resource constraints, requires separate analysis. Finally, the future lies in studying the role of emerging platforms such as the metaverse and super-apps, and their potential in shaping the next generation of digital customer experience.

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Using Artificial Intelligence to Ensure Information Security of Organizations: Possibilities, Problems and Prospects

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Abstract. The article substantiates the relevance of studying the possibilities of using artificial intelligence in the information security of organizations, which is determined by the need to increase the level of protection, improve response to incidents and reduce the risks associated with cyberattacks. For this purpose, statistics on global threats to information security are analyzed based on the number of incidents in 2023 and 2024. On this basis, the main tasks of AI technologies in ensuring the information security of organizations and their content are formulated. The article analyzes the capabilities of AI solutions at individual stages of information security: warning and forecasting threats; penetration testing and attack simulation; detection of malicious and abnormal activity; processing of security events; recognition of phishing, unwanted content, dangerous sites, etc. As a result of the analysis, several levels of AI technology use in ensuring information security are identified: AI is already being used, AI can be used, the use of AI is not justified or will not bring significant benefits. The study highlights such prospects for using AI in the field of information security as the creation of autonomous systems based on AI and modeling a cyber range, and also considers problems associated with the complexity of implementing AI technologies in this area.

Keywords. Information security, threats, artificial intelligence, technologies, organizations

1. Introduction

The relevance of studying the possibilities of using artificial intelligence (AI) in the information security of organizations is determined by the need to increase the level of protection, improve response to incidents and reduce risks associated with cyber threats.

The possibilities of artificial intelligence technology in ensuring information security of organizations are determined by many factors, the main ones of which are [1, 2, 3]:

- increase in cyber threats. With the rise of digitalization and the transition to remote work, the number of cyberattacks has increased significantly. Hackers are using increasingly sophisticated methods, which requires organizations to take new approaches to protecting information.

- Big data processing. AI is able to process and analyze huge amounts of data in real time, which allows identifying anomalies and potential threats faster and more effectively than traditional methods.

- process automation. Using AI in information security allows you to automate routine tasks such as system monitoring, log analysis, and incident response, freeing up resources for more strategic tasks.

- predictive analytics. Machine learning algorithms can predict potential threats based on historical data, allowing organizations to defend against attacks.

- improving threat detection. AI can improve threat detection by using algorithms that learn from previous incidents and can adapt to new attack methods.
- regulatory compliance. With the increasing number of regulatory requirements for data protection, using AI can help organizations effectively manage risks and comply with the necessary standards.
- reducing costs. Implementing AI in information security processes can reduce security costs by increasing efficiency and reducing the number of false positives.
- security innovation. AI opens up new opportunities for developing innovative solutions in the field of data protection, such as biometric authentication, intelligent access control systems, and others.

The purpose of the study is to analyze the possibilities of using AI technologies applied in the field of information security, to study the problems in this area and to assess the prospects for using artificial intelligence to improve the level of information security of organizations.

2. Modern threats to information security of organizations

The number of incidents in 2023 and 2024 (Fig. 1), data on which are presented in the study by Positive Technologies (PT) [4], testifies to the global threats to information security.

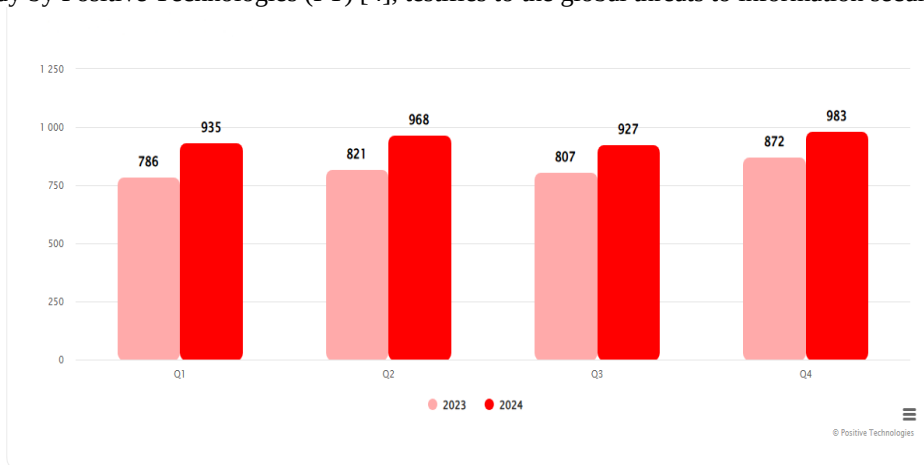


Fig 1. Number of incidents in 2023 and 2024 (by quarter)

According to PT Expert Security Center [4], in the fourth quarter of 2024, the number of incidents increased by 5% compared to the previous quarter and by 13% compared to the same period last year. Malicious software (malware) is the main tool of attackers: it was used in 66% of successful attacks on organizations and 51% on individuals. Ransomware (42%) and remote-control malware (38%) were most often used against organizations, while spyware (48%) was used against individuals. There was an increase in interest in spyware in attacks on organizations (20%, 4 percentage points more than in the previous quarter). During the period under review, confidential information was disclosed as a result of 53% of successful attacks on organizations, and disruption of the organization's core business was observed in 32% of incidents.

Figure 2 provides information on the industry affiliation of organizations that are victims of cyberattacks in 2024 [4]. It should be noted that 3% of successful attacks were directed at transport organizations [5].

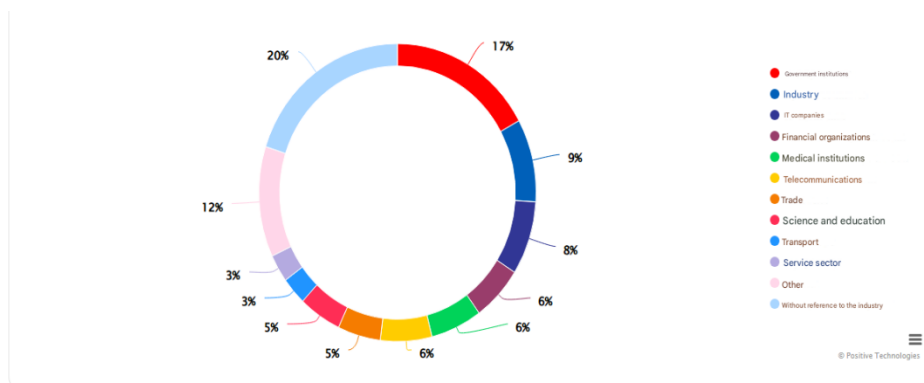


Fig. 2. Organizations that are victims of cyberattacks in 2024

Data on the malware tools used in hackers' arsenals in successful attacks on organizations and individuals in the fourth quarter of 2024 are shown in Figure 3 [4].

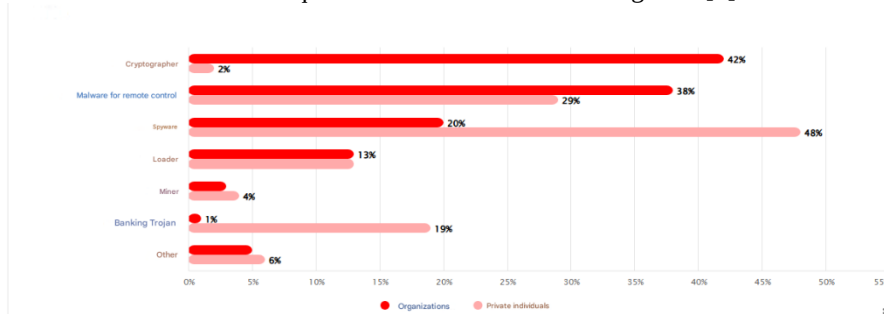


Fig. 3. Share of successful attacks using malware in the fourth quarter of 2024

In the fourth quarter of 2024, ransomware (42%), remote control malware (38%) and spyware (20%) were most often used in successful attacks on organizations. Ransomware continued to be a relevant threat to organizations around the world and was actively used not only for financial gain, but also to cause damage for hacktivist purposes.

In successful attacks on individuals in the fourth quarter of 2024, the trend towards using spyware (48%) and an increase in interest in banking Trojans (19%, 8 percentage points more than in the previous quarter) was observed.

The share of remote access malware in successful attacks on organizations and individuals in the fourth quarter of 2024 decreased by 6 percentage points compared to the previous quarter and amounted to 38% and 29%, respectively [4].

3. Possibilities of using artificial intelligence technologies in ensuring the information security of organizations

Let us consider the main tasks of using AI in ensuring information security, as well as defense tactics and technologies that use artificial intelligence.

AI technologies make it possible to solve many problems at all stages of preparation for repelling an attack, as well as during detection, response, and liquidation of the consequences of an incident. Each application can be attributed to one of three main tasks: reducing the workload of cybersecurity specialists, detecting anomalies in the behavior of

users, applications, and systems, advanced threat detection, and automation of defense systems [6]. Table 1 presents the main tasks of AI technologies in ensuring the information security of organizations and their content [7].

Table 1. Main tasks of AI technologies in ensuring information security of organizations and their content

Tasks	Contents
1. Reducing the workload and helping specialists	Using AI technologies in security solutions, it is possible to automate routine processes of primary processing of security events and other information that specialists are currently forced to analyze. In addition, chatbots based on large language models (LLM) can provide operational support to specialists in the decision-making process to counter cyber threats.
2. Threat and incident detection	AI technologies, processing large volumes of data, allow identifying malicious actions, non-standard behavior of users and systems, and providing early warning of incidents. In this case, such data as logs are used - files that record events of network equipment and servers, telemetry of end devices, network traffic, authentication data, and others. The following methods are used to detect anomalies and advanced threat detection: machine learning and statistical analysis, graph methods, sequence analysis, anomaly detectors, and others.
3. Incident Investigation and Response Automation	AI-based solutions can automate not only attack detection processes, but also decision-making, response, and incident prevention. AI technologies can be used to speed up investigations, collect context, and automated response measures. For this purpose, such methods as automated playbooks, ML optimization of investigation routes, and incident categorization scenarios are used. In this way, automated or semi-automated measures (device isolation, account blocking, file quarantine) are implemented, the average response time is accelerated, the share of automated incidents and the percentage of closed incidents without manual intervention are increased.

Table 2 presents the capabilities of AI technologies at individual stages of information security [7].

Table 2. Capabilities of AI technologies at individual stages of information security

Stages	Capabilities
1. Warning and forecasting of threats	AI technologies can automatically detect attempts to unauthorized access to systems and networks, reducing incident response times. Machine learning algorithms can use historical and observational data to predict future attacks and vulnerabilities, allowing organizations to take proactive measures to protect themselves.
2 Vulnerability Management	AI can help assess software and system vulnerabilities, suggesting prioritized actions to address them. For vulnerability assessment, AI can automatically scan systems and applications for known

	vulnerabilities, using vulnerability databases and machine learning algorithms to identify potential weaknesses. For organization security analysis AI can analyze the configurations of an organization's systems and networks, identifying misconfigurations or deviations from best practices that could lead to vulnerabilities.
3 Penetration testing and attack simulation	Conducting penetration tests with AI technologies can automate the penetration testing process by simulating the actions of attackers and identifying vulnerabilities in the system that can be exploited for unauthorized access. AI can help in risk assessment by analyzing various factors, such as the likelihood of an attack and the potential consequences, which allows organizations to make more informed decisions about security measures. Generative AI can be used to create a set of the most likely passwords for a specific target, analyze text files of the system under test, and generate an understandable report on the results of the attack simulation.
4 OSINT (open-source intelligence) of current cyber threats	AI technologies can significantly improve open-source intelligence (OSINT) processes and help identify relevant cyber threats to ensure information security in the following ways: - automated data collection. AI can automate the process of collecting information from various open sources, such as social media, forums, blogs, news sites, and vulnerability databases. This allows for quick and efficient collection of relevant data on current threats; - big data analysis. AI can process and analyze large amounts of data, identifying patterns and trends that may indicate new cyber threats. This includes using machine learning algorithms to classify and predict threats; - anomaly detection. AI can identify anomalies in user or system behavior that may indicate potential threats. For example, a sharp increase in discussions about a certain vulnerability or attack may be a signal that deeper analysis is needed; - sentiment analysis. AI can conduct sentiment analysis of open-source texts to determine public opinion on specific threats or incidents. This can help in assessing the level of risk and community response to specific cyber threats; - threat geolocation. Using geographic data, AI can visualize the distribution of threats in different regions, which helps organizations better understand the risks based on their location; - mention monitoring. AI can track mentions of specific companies, technologies, or vulnerabilities in open sources, providing timely notifications about new threats or incidents; - social media analysis. AI can analyze social media data to identify potential threats related to cyberattacks, including identifying attackers and their modus operandi.
5 Code verification	AI technologies offer a variety of options for code review to ensure information security:

	- static code analysis. AI can be used for automated static code analysis, identifying vulnerabilities and potential errors in software before it is executed. Algorithms can learn from known vulnerabilities and patterns to find similar problems in new code; - dynamic analysis. AI can help in dynamically analyzing applications during their execution, monitoring the program's behavior and identifying anomalies that may indicate vulnerabilities or attacks; - natural language processing. AI can analyze code documentation and comments to identify potential problems or flaws in logic that can lead to vulnerabilities; - automated testing. AI can generate test cases based on code analysis, allowing for more efficient testing of application functionality and security; - learning by example. Machine learning algorithms can learn from existing code and security incident data to improve their predictions and find new types of vulnerabilities; - monitoring code changes. AI can monitor changes in the code base and automatically check new commits for potential security issues; - recommendations for fixes. Based on code analysis, AI can provide recommendations for fixing found vulnerabilities, making it easier for developers to eliminate them; - identifying code patterns. AI can identify code patterns that often lead to vulnerabilities and suggest best practices for avoiding them.
6 Control of confidential data	AI technologies can be useful for controlling confidential data in ensuring information security in the following areas: - classification and identification of sensitive data; - automated recognition of personal data, financial information, organizational secrets, etc. in texts, files and databases; - detection of attempts to transfer confidential information via channels, in the cloud, in messengers, to external media; - unusual access patterns, attempts to copy data, unusual hours of activity, combinations of users and resources; - risk-based access control and risk assessment of each access request, multi-factor and contextual authentication, dynamic access rights; - context-dependent use of encryption, replacement of confidential values with tokens, masking for developers and testing; - automated incident detection and generation of response actions; access control and security policies for large cloud services; - data traceability and data management, automatic tracking of data sources, transformations and usage for auditing and compliance with information security requirements; - automatic removal or replacement of sensitive elements in documents and messages. All these capabilities have the potential to protect against confidential data leakage, the most common (54%) consequence of cyberattacks on organizations in 2024 [8].
7 Detection of malicious and	The use of artificial intelligence in protecting organizational information systems involves the automatic analysis of large volumes

abnormal activity, unknown threats	of data (logs, network traffic, security events, end-device telemetry, etc.) to detect malicious and abnormal activity, speed up responses, and improve detection accuracy compared to traditional signature-based methods (classic virus detection methods based on comparing files with a database of known virus signatures). At this stage, AI solves the following information security problems: - detection of known and unknown malicious objects: malware, account compromises, C2 activity (Blocking C&C traffic or "dismantling" an attacker's C2 infrastructure can stop a cyberattack), zero-day exploits (a type of malware) through behavioral characteristics; - detection of anomalies and deviations: unusual user behavior patterns, sudden changes in traffic, authorization logs, access to data; - detection of unauthorized actions and abuses: suspicious financial transactions, phishing and malicious attachments, credential manipulation; - early warning and reduced response time: accelerated incident identification, automatic correlation analysis between different data sources; - decision support in SOC (Security Operation Center): assisting analysts with explainable conclusions, automatic context collection and response recommendations.
8 Handling security events	According to Microsoft [9], SOC teams receive an average of 4,484 alarms per day and spend about 3 hours manually separating real threats from the noise. At the same time, it takes a SOC employee about 10 minutes to process and analyze each event. In such conditions, false positives become a problem, which inefficiently spend the efforts and time of specialists, as a result of which they can miss a real attack. False positives occur due to the fact that some actions of intruders can be disguised as legitimate user activity. The use of artificial intelligence can potentially solve the problem of SOC overload. An AI solution will be able to conduct an initial sorting of security events, remove likely false positives and highlight incidents that really require attention for a specialist. The use of AI technologies will significantly (according to IBM estimates, twice) speed up the sorting and processing of security events, and therefore increase the overall efficiency of the SOC [9].
9 Access analytics and behavioral analysis (UEBA – User and Entity Behavior Analytics)	Behavioral analysis in information security is an approach that relies on modeling the normal behavior of users and other objects (devices, applications, services) and identifying deviations from it as potential threats. Its goal is to detect account compromise, insider threats, illegal data movement and other types of abuse earlier. To implement it, the behavior of: users (logins, time and place of login, attempts to access data, sequences of actions); objects (devices, servers, cloud services, applications, containers); networks and applications, workflows and anomalies in access to resources and data. Practical examples of such behavior may be: unusual login activity outside working hours from a new device or from a different geolocation, and then access to sensitive data; a step-by-step chain of

	actions: login → access to critical files → copy to external media or upload to the cloud; a sudden increase in outgoing network traffic from the server or non-standard requests to the cloud service API. Using this approach with machine learning technologies, it is possible to create a profile of the normal operation of an object, such as a user, system or network, from which deviations (anomalies) may indicate the actions of a cybercriminal. As a result, this can lead to early detection of anomalous behavior, insider threats and account compromises, reducing the time to detect threats and respond.
10 Recognition of phishing, unwanted content, dangerous sites	Social engineering remains one of the main methods of cybercriminals in 2024, it was used in every second attack on organizations. Moreover, in 42% of attacks using malware, the delivery channel was phishing emails [4]. Cybercriminals manipulate the emotions of victims to achieve their goal, so in protecting against phishing, employee training alone is not enough: anyone can make a mistake and not check a malicious email. AI can help at different levels of protection against phishing and dangerous sites - from URL and page content analysis to user behavior and network signals. Together, such solutions provide early warning, automatic blocking and clear explanations to the user. For this, machine learning technologies are used that implement URL analysis and page features (URL length, number of subdomains, use of suspicious domain suffixes, presence of words frequently used in phishing, domain age, ownership history, IP address) and allow determining the likelihood of risk and the threshold blocking signal. The use of such an approach can help reduce the risk of early phishing through rapid online risk assessment and automatic blocking; provide comprehensiveness (URL, content, visual authenticity and reputation in one solution); increase flexibility (can be adapted for web feeds, email (for attachments/links) and mobile serial traffic); the ability to learn from real users through feedback, improving accuracy over time.
11 Reaction	Modern AI technologies can significantly speed up incident response and increase organizational resilience through the following solutions: - early detection and accelerated investigation; - ML algorithms for UEBA and behavioral analytics detect anomalies in user and entity behavior, combine signals from different sources and reduce the number of false positives for incidents; - response with automatic rule application: node isolation, account blocking, firewall rule update, blocking malicious IP addresses; - automation of routine remediation actions: revert changes, change keys/passwords, stop malicious processes; - quick verification of backup integrity, automatic restoration of a safe version, audit of changes; - post-incident analysis based on ML: determining the causes of the violation, assessing the impact and steps to prevent recurrence. Such support allows specialists to obtain the necessary data about a security incident much faster, and therefore make a decision more quickly. One of the promising areas is training organizations' own LLM

	cybersecurity assistants, who, if cybercriminals were able to achieve the goals of a cyberattack, can potentially help cope with the consequences of the incident and suggest optimal actions to eliminate the damage caused.

An analysis of the information security capabilities considered in Table 2, including various solutions, allows us to divide them into three levels depending on whether they use artificial intelligence technologies: AI is already used, AI can be used, the use of AI is not justified or will not bring significant benefits.

Thus, the capabilities of AI in information security are quite broad, but even with further development of the technology, there are still unused areas of protection.

4. Problems of using AI technologies in ensuring information security of organizations

High expectations for the use of AI technologies in information security face a number of challenges related to the cost and complexity of their implementation: scarce and high-quality training data is required; only highly qualified specialists with certain skills and competencies can create such a product; the use of AI solutions requires significant computing power, which may be unavailable to organizations for various reasons and / or require significant support from the business.

There is also a risk of excessive automation: not every decision should be made automatically. In combination with the competent expertise of a human analyst, it is important to ensure the correct interpretation of the results.

It is necessary to consider the security of the model itself, protection against leakage of confidential information and prevention of abuse of generative AI models.

Regular audit of models is necessary for deviations and false positives. In addition, there are ethical and legal frameworks: attack modeling should only take place in authorized environments with clear restrictions and access control.

5. Prospects for using AI technologies in ensuring information security of organizations

Research in the field of information security highlights the following trends in the use of AI in this area [7,10]:

Autopilot. An autonomous system based on AI ("autopilot" in the context of information security) can improve the protection of an organization due to the following capabilities:

- rapid response to incidents: automatic detection, prioritization of threats and execution of predefined actions without delays;
- increased coverage and accuracy: continuous monitoring 24/7, reduction of omissions and errors due to human fatigue;
- standardization of response: uniform schemes for actions to automate response (playbooks) and approaches to incidents, minimization of variability of actions;
- effective risk management: early detection of abnormal behavior, vulnerabilities and configuration errors, predictive analytics on threats;
- resource savings: reduced load on SOC/IT departments, redistribution of people to more complex tasks;

- improved decision making: explain ability of decisions (when necessary) and transparent action logs for audit and compliance.

Cyber Range Modeling. A cyber range is an isolated, controlled environment that simulates real networks, applications, and data for training employees and testing defenses. Using AI technologies in such modeling allows for automatic creation of attack scenarios, generation of realistic traffic, adaptive adjustment of defenses to the evolution of threats, and acceleration of training and testing of information security measures.

AI improves the efficiency of cyber range modeling in the following ways:

- threat and attack scenario modeling. AI can automatically generate a variety of attack scenarios and their variations (different tactics, techniques, and procedures). Generative models can create new attack variants to test the resilience of defenses to previously unknown scenarios, within an ethical and controlled environment.

- generation of realistic data and traffic. Machine learning maintains the realism of the load: artificial but plausible traffic and user events. This allows testing SOC operations and detection methods in the absence of real incidents.

- detection, analysis and automatic response. Behavioral analytics models identify unusual patterns and early signs of attacks.

Within the cyber polygon, AI can help with incident prioritization, automatic early detection, and response management (automated isolation, blocking, and escalation scenarios). It can safely explore which security settings work against potential attackers. AI agents can act as an adaptive “red team,” trying to bypass defenses, but within a safe environment and ethical constraints. This approach accelerates the search for weak points, testing of regulations, and increasing the resilience of response processes. In addition, AI optimization of training scenarios is possible: adjusting the complexity depending on the level of employee training, automated generation of reports after training to improve further actions.

6. Conclusion

Thus, the study of the possibilities of using AI in information security is relevant and necessary to improve the level of protection of organizations in the context of modern digital development of society.

Analysis of the possibilities of using AI technologies and methods applied in the field of information security helps to identify their potential and effectiveness, as well as the creation and testing of new algorithms and models based on AI to improve the level of protection of organizational information from cyber threats.

Despite a wide range of possible tasks for AI, a person in the field of cybersecurity is still irreplaceable. Even with a level of technology that is significantly superior to today, there will still be many tasks for a specialist, such as developing a general defense strategy, monitoring and managing the operation of AI tools, and solving complex and non-standard issues. In the future, the ability to effectively work with AI tools will become an important component of the necessary competencies of an information security specialist.

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NVivo Application for Qualitative Data Analysis in Scientific Research: Options and Result Visualizations

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Abstract. The paper analyzes how NVivo application uses advanced tools for data organization, thematic analysis, and graphical representation of research findings from qualitative studies in the social and economic sciences. A special attention is given to NVivo's charts, models and word maps that supports the interpretation and communication of research findings. The research concludes that NVivo represents a valuable resource for increasing analytical quality of scientific work and effectively presenting complex qualitative results of research findings. The article was elaborated within the Project selected in competition "Stimulating excellence in scientific research 2025-2026" 25.80012.0807.37SE "The perfection of instruments for reducing income inequality and reducing poverty of the population in the process of European integration of the Republic of Moldova".

Keywords. software, application, data, analysis, visualization.

1. Introduction

Qualitative research in social and economic sciences often generates large volumes of unstructured data – interview transcripts, focus group discussions, open-ended survey responses, field notes, etc. Analyzing such data manually can be laborious and prone to bias. NVivo is a Computer-Assisted Qualitative Data Analysis Software (CAQDAS) designed to help researchers organize, code, analyze, and interpret these unstructured datasets.

Before tools like NVivo, qualitative analysis relied on physical methods (e.g. highlighters, scissors, index cards) to mark and sort themes, which was time-consuming and made it difficult to manage complex projects. NVivo provides a centralized digital workspace where all data sources (text, audio, video, PDFs, images) can be imported and managed within a single project. This centralization and organization allow researchers to handle dozens or even hundreds of documents systematically, maintaining a clear audit trail of the analysis process. NVivo became especially popular in academic research, government and policy studies, and lengthy interview-based projects, filling a gap for more rigorous and efficient qualitative analysis tools.

Over the past decades, NVivo has evolved into a leading QDA software. It not only supports basic tasks of coding and retrieving text segments, but also offers advanced features for linking data, shaping ideas, and even modelling relationships between concepts. The use of NVivo and similar CAQDAS has been shown to enhance the quality and systematic nature of qualitative analysis. By automating routine tasks (like grouping excerpts by code or searching for keywords), NVivo frees up researchers' time to explore deeper patterns and interpretations in the data.

Ultimately, tools like NVivo aim to make qualitative analysis more rigorous without sacrificing the richness and context that are the hallmarks of qualitative inquiry. This article provides an overview of NVivo's capabilities in qualitative data analysis, with special attention

to its options for data organization, thematic coding, and the visualization of results through charts, models, and “word maps” (word-based visualizations).

2. Literature review

The academic literature on qualitative methodology has increasingly acknowledged the value of CAQDAS tools like NVivo. NVivo is one of the most widely used QDA software packages and has been cited as the de facto choice for many qualitative researchers due to its extensive features and proven utility (QSR International, 2026). Early qualitative analysis software (such as NUD*IST in the 1980s) laid the groundwork for NVivo, which was developed as an improved successor with enhanced capabilities (e.g. allowing rich text handling, multimedia support, and collaborative work). NVivo’s design is intentionally methodology-agnostic, meaning it can be applied to a range of qualitative approaches including grounded theory, phenomenology, discourse analysis, ethnography, content analysis, and mixed-methods research. This flexibility has made NVivo applicable in diverse fields from health care and education to sociology and economics.

Multiple sources have noted that using NVivo can increase the efficiency and quality of qualitative analysis (Bazeley & Jackson, 2013) (Silver & Lewins, 2014). Maher et al. (2018:1) highlight that NVivo “provide[s] excellent data management and retrieval facilities that support analysis and write-up” by easing the manual labour of coding and sorting data. The software replaces tedious manual tasks (cutting and color-coding piles of transcripts) with more efficient digital operations, allowing the researcher to focus on interpreting meaning rather than on data management mechanics. As a result, the analysis process becomes more systematic and transparent. NVivo maintains a searchable database of all coded excerpts, memos, and links, which contributes to the auditability of qualitative research – an important criterion for rigor. Additionally, NVivo supports teamwork by providing project merge tools and collaboration features. Researchers working in separate NVivo project files can merge their coded data into one master project, making NVivo ideal for team-based qualitative projects where multiple analysts are involved. This capability helps ensure consistency in coding and allows cross-validation of findings among team members.

Despite its benefits, the literature also discusses challenges in using NVivo. A commonly cited issue is the steep learning curve. Mastering NVivo’s interface and features often requires formal training or significant practice, which can be a barrier for new users or those outside academia. NVivo is fundamentally a powerful data management and facilitation tool, but the intellectual work of analysis – identifying themes, interpreting patterns, drawing conclusions – remains with the researcher. As Zamawe (2015:13) puts it, “unlike statistical software, the main function of CAQDAS is not to analyse data but rather to aid the analysis process, which the researcher must always remain in control of”. This is a critical point to dispel the misconception that qualitative analysis can be fully automated. Researchers must still apply their theoretical lens and contextual understanding. NVivo simply provides an organized framework to do so more efficiently and systematically. Some authors also warn about potential overreliance on code frequency or query outputs – just because a theme is mentioned frequently (as NVivo’s queries might show) does not automatically mean it is the most important insight in the study. Qualitative analysis requires nuance and considering context, something NVivo outputs cannot determine on their own (Knafllic, 2015).

Numerous published studies have documented using NVivo to strengthen qualitative analyses. For instance, in policy and program evaluation research, NVivo has been used to manage large sets of interviews and focus group data, making it easier to trace how conclusions were derived from raw data. Health researchers have utilized NVivo to maintain rigor in literature reviews and meta-syntheses by systematically coding findings from many sources.

In dissertation and thesis work NVivo help students handle extensive qualitative datasets and maintain consistency over long research projects. NVivo's role in mixed-methods research is to combine qualitative interview analysis with quantitative survey data by using classification and query features to compare groups or to integrate quantitative attributes (like demographic data) with qualitative themes. Overall, the literature suggests that when used appropriately, NVivo can improve the depth and transparency of qualitative analysis, though it requires careful methodological consideration and researcher skill to fully capitalize on its capabilities.

3. Methodology

This article employs a descriptive and exploratory approach to examine NVivo's options for qualitative data analysis and result visualization. It was conducted a review of NVivo's software documentation, user guides, and relevant methodological literature to outline the key features of the application. The focus is on NVivo 12 and later (including NVivo 15/Lumivivo) as used in typical social science research projects. In addition, it was drawn on example use cases from existing research to illustrate how NVivo's tools are applied in practice.

For the purposes of illustration, it can be considered a hypothetical qualitative study on economic inequality in a community – involving data from interviews, focus groups, and field observations. Using such a scenario, we can walk through the stages of using NVivo to manage and analyze the data. All qualitative data (transcribed interviews, focus group transcripts, observation notes, relevant policy documents, etc.) are imported into NVivo as Sources. NVivo supports importing a wide variety of formats including text documents, PDFs, audio/video files (with or without transcripts), spreadsheets, and even social media content. Once in NVivo, these sources can be organized into folders or sets (e.g. grouping all interviews in one folder, focus groups in another). Researchers can also create case nodes for each interviewee or participant and assign demographic attributes (age, gender, etc.) to those cases. This structure allows for later comparisons across different participant groups. The organizational capability of NVivo ensures that no data get lost and that one can easily navigate between raw data and emerging themes. Coding is at the heart of qualitative analysis, and NVivo's interface is built to streamline the coding process. Users create nodes in NVivo which represent codes, themes, or concepts. These nodes can be arranged in a hierarchical tree (parent themes and sub-themes) or kept as free nodes for open coding. To code data, one simply highlights text (or time segments in audio/video) and assigns it to one or more nodes. NVivo's coding tools allow for both deductive coding (applying a predefined code framework) and inductive coding (creating new codes as patterns emerge from the data). The software tracks all coding actions – a piece of text coded at a node can be retrieved by opening that node to see all references in one place. This makes it easy to gather all evidence for a particular theme when it comes to analysis and writing. Memos can be written alongside to capture analytic insights or reflexive notes during coding. NVivo's ability to handle overlapping codes and to merge or reorganize nodes on the fly gives researchers flexibility as their understanding evolves. The end result of coding is a structured categorization of the qualitative data, which is the basis for deeper analysis. NVivo offers powerful query tools that enable asking complex questions of the coded data. For example, a Word Frequency Query can list the most common words or phrases in the text, which might hint at prevalent topics. A Text Search Query can find all instances of a particular term or phrase across the dataset (useful for checking how often certain concepts appear and in what context). More advanced queries include the Coding Query (to retrieve content coded at combinations of nodes, e.g. where "economic policy" and "education" co-occur) and the Matrix Coding Query, which can cross-tabulate two sets of categories (for instance, comparing themes across male vs. female participants, or across different focus groups). These query

results can be viewed in tabular form or exported. Such exploration helps in discovering patterns that might not be immediately obvious – for instance, one might find that certain themes are mentioned predominantly by a particular demographic group, or that some concepts frequently appear together, indicating a potential relationship worth investigating. By iteratively querying the data, researchers refine their insights and ensure that their interpretations are grounded in evidence from the dataset. If multiple researchers are coding data, NVivo includes tools for comparing coding consistency. The Coding Comparison Query can measure inter-coder reliability by checking the agreement on coding between different team members. In team settings, NVivo's Collaboration Cloud or server options enable multiple coders to work on the same project concurrently, or to periodically merge their work, as mentioned earlier. This methodological step is important for enhancing the credibility of the analysis in scientific research – high agreement on coding indicates that the themes are not just subjective to one analyst but are consistently observed. Any discrepancies can be discussed and resolved to refine the codebook. This methodology (data organization → coding → querying → team validation) sets the stage for producing meaningful results. With the dataset thoroughly coded and examined, we can now leverage NVivo's visualization features to represent the findings in a clear and compelling way.

4. Results

In the **Table 1** it is highlighted that Computer-Assisted Qualitative Data Analysis Software (CAQDAS) differs not only in technical capabilities but also in the research philosophy they best support. NVivo, ATLAS.ti, and MAXQDA emerge as comprehensive platforms suited for large, complex projects requiring deep coding, visualization, and mixed-methods integration. These tools are particularly appropriate for institutional research, doctoral work, and projects involving extensive datasets and advanced querying. In contrast, tools such as QDA Miner, Dedoose, and Quirkos prioritize accessibility, intuitive interfaces, and ease of learning, making them suitable for small-scale studies, teaching contexts, or teams requiring rapid onboarding. Their limitations appear mainly in advanced querying power and scalability for large multimedia datasets.

Open-source solutions (KH Coder, RQDA, Taguette, and Casandra) provide cost-effective alternatives, especially for researchers with technical skills or budget constraints. However, they often require greater methodological and technical expertise and may lack the polished interfaces and multimedia integration found in commercial platforms. Overall, the choice of CAQDAS should be guided not by popularity but by the nature of the research design, team capacity, data complexity, and the balance between analytical depth and usability.

Returning to NVivo software, after applying it to analyze the qualitative data, the findings can be organized around major themes and supported by visual representations. NVivo's advanced visualization tools – charts, models, and word-based maps – prove especially useful in interpreting and communicating the results of qualitative analysis. These visualizations translate the coded data and queries into accessible graphics, helping to summarize complex information and reveal patterns at a glance.

Using NVivo, can be identified several overarching themes, for example, regarding income inequality. For instance, common themes might include "Employment" and "Income", "Education" and "Skills", "Health", "Policy" and "Support". Each of these can have multiple sub-themes (e.g., "informal employment", "access to training programs", "healthcare access," etc.), which are organized in NVivo as hierarchical nodes. The coding process results in a tree of nodes reflecting the complexity of the issue. NVivo's coding stripes and node frequency counts shows which themes are most referenced across interviews. For example, "Employment" may appear in nearly every interview, whereas a theme like "Digital" may be

mentioned in only a few focus groups, indicating it is a less universal but still notable issue. This frequency information is automatically tallied by NVivo and can be visualized.

Table 1. Comparative overview of major CAQDAS (Computer-Assisted Qualitative Data Analysis Software) tools: strengths, limitations, and recommended use cases

Software	Strengths	Limitations	Use
NVivo	Handles text, audio, video, images, social media; strong querying (Boolean, matrix coding); rich visualizations; large user community	Expensive; steep learning curve; Mac version lags; project merging can be tricky	Comprehensive qualitative projects needing deep coding & visualization
ATLAS.ti	User-friendly interface; strong network visualizations; robust coding; multimedia support; good collaboration tools	High cost; some advanced queries less powerful than NVivo	Researchers who want visual, intuitive exploration of qualitative data
MAXQDA	Supports qualitative + mixed-methods; survey & statistical integration; strong longitudinal analysis; intuitive interface	Full version expensive; some advanced queries less deep than NVivo	Mixed-methods research, combining qualitative and quantitative
QDA Miner + WordStat	Strong text + quantitative analysis; statistical content analysis; integrates with surveys	Less focus on multimedia; user interface less modern	Mixed-methods, content analysis with quantitative/statistical needs
Dedoose	Web-based; cross-platform; good for distributed teams; balances ease and features	Internet-dependent; privacy concerns; less suited for huge datasets	Collaborative teams, cross-platform qualitative analysis
Quirkos	Very simple, intuitive, visual interface; fast learning curve	Limited advanced querying; weaker on large projects or multimedia	Small-scale projects, beginners, teaching
KH Coder (open source)	Text mining, clustering, co-occurrence analysis; free	More technical; limited multimedia; steep learning for non-coders	Large text corpora, researchers with coding/statistical background
RQDA (open source, R-based)	Free; integrates with R for powerful workflows	Limited interface; R knowledge required; development not always active	Researchers comfortable in R, reproducible coding
Taguette (open source)	Free, simple, easy for text-only coding	Few advanced features; text only	Budget-limited projects, teaching, simple coding
Cassandre (open source)	Collaborative (Cassandre); free	Interfaces less polished; fewer updates	Budget-conscious teams, experimental or academic use

Source: elaborated by authors

One of NVivo's classic visualization tools is the chart view. A chart of coding references by theme can be generated to see the distribution of data across the major categories. NVivo allows users to create bar charts or pie charts based on coding frequency or

coverage for selected nodes. For example, a bar chart illustrated, for instance, that “Employment” and “Support” had the highest number of references (indicating its prominence in discussions), followed by “Digital” and “Access”, and with “Capacity” being the least referenced theme. This chart provides a quick quantitative snapshot of qualitative findings – a helpful way to validate that the analysis covered all major areas and to communicate which topics were most salient to participants (it is important to note, however, that frequency is not the sole indicator of importance; even less frequent themes can be critical, which is why they are interpreted within context).

To get a sense of the language and emphasis used by participants, we conducted a word frequency query on some interview transcripts. The query results were used to create a word cloud (sometimes called a “word map”). Figure 1 shows an example of an NVivo word cloud generated from qualitative text. In a word cloud, the size of each word corresponds to how often it appears in the corpus.

In our analysis, the word cloud highlighted prominent terms such as “employment”, “digital”, “support”, and “access”, suggesting these concepts were central in participants’ discussions. NVivo automatically filters out common stop-words (like “and”, “the”, “is”) unless configured otherwise. Using word clouds in qualitative research helps in highlighting the prominent terms and key themes in research, simplifying the presentation of core findings. We found this to be true: the word cloud provided an intuitive visual summary of what issues were most frequently talked about, which was a helpful starting point for deeper analysis and for explaining results to stakeholders who might not read the full report. It served as a conversation piece to quickly convey the focus of discussions before delving into detailed results.

NVivo also enables researchers to visually map relationships between concepts using models or maps. We utilized NVivo’s modeling tools to create a concept map of how different factors related to income inequality interact. Figure 2 illustrates a simplified example of an NVivo concept model (network diagram) showing key concepts and their interconnections.

In our result, the model revealed, for instance, that Education Level was linked to Employment Opportunities, which in turn was connected to Income Stability. We also linked Policy Support as an overarching factor that influences both education and jobs (for example, government training programs affecting employment prospects). NVivo’s models are essentially mind maps or concept maps created within the software’s “Model Editor”, allowing the researcher to drag and drop nodes (which can represent themes, cases, or any project item) and draw connections or arrows to denote relationships. This visual representation supported our analysis by making implicit relationships explicit. Models in NVivo map connections between concepts, uncovering relationships that might not be apparent in text-based analysis. In other words, by arranging concepts visually, we could better see the network of influences in a way that a linear text list of themes might not reveal. The model serves as a hypothesis of how things are connected, which we can then compare against the data (e.g., checking if participants who discussed “Education” also mentioned „Employment”, etc., which NVivo can facilitate through query cross-tabs).

In addition to word clouds and concept maps, NVivo provides several other visualization options that can be leveraged for a comprehensive view of results. For example, we used a hierarchy chart (tree map) to visualize the relative size of sub-themes under each major theme, based on number of references. This quickly showed which sub-topics were most discussed within a theme. We also tried NVivo’s cluster analysis on the interviews to see if any interviews grouped together based on thematic similarity – NVivo’s cluster dendrogram suggested patterns (for instance, perhaps interviews from rural participants clustered separately from urban participants because of different issue emphasis). While such

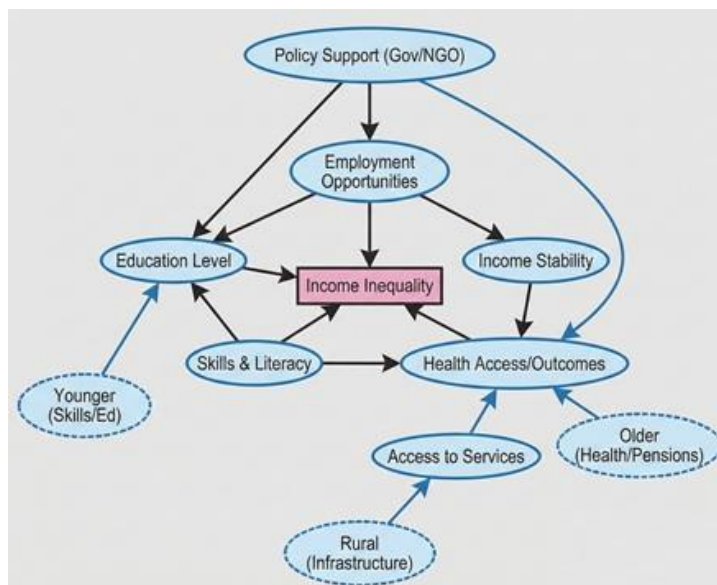


Figure 2. NVivo concept model of the interconnections between key themes related to income inequality

Source: Elaborated by authors

Note: The diagram illustrates how “Policy Support (Gov/NGO)” influences “Employment Opportunities”, which in turn affect “Education Level” and “Income Stability” and contribute to “Income Inequality”. The model also shows how “Skills & Literacy”, “Health Access/Outcomes”, and “Access to Services” interact within this system, while contextual factors such as “Young (Skills)”, “Older (Health/Pensions)” and “Rural (Infrastructure)” shape participants’ experiences. Arrows indicate the direction of influence between concepts as identified through qualitative analysis.

5. Discussions

All the findings are enriched and validated through NVivo’s tools. The software ensures that every conclusion drawn could be traced back to multiple raw data excerpts, enhancing the credibility of the results. The results illustrate not only the substantive findings about the example topic but also how NVivo’s features enhance the analytical process and presentation of qualitative research. One of the clear benefits observed is that NVivo allows researchers to engage with their data more deeply and systematically. By using tools like queries and models, with NVivo can uncover patterns and relationships that may have been missed with a purely manual analysis. For instance, the ability to swiftly retrieve all instances of a concept across dozens of documents or to visualize co-occurring themes pushes the researcher to consider connections in the data that are not immediately obvious. This aligns with the view that integrating data visualization into qualitative analysis can help “challenge conventional approaches” and encourage researchers to rethink assumptions. A concept map is a case in point – creating a visual model of how themes relate forced us to explicitly theorize the interplay between factors, which strengthened the analysis. Additionally, NVivo’s mixed-methods capacity (e.g., allowing quantitative attributes and qualitative data to be linked) gives a richer perspective. It can, for example, quantitatively show variations in theme prevalence by group, adding a layer of empirical rigor to qualitative findings.

A major challenge in qualitative research is conveying dense, text-based findings to stakeholders (e.g., policymakers, community leaders, or even other researchers) in an accessible way. NVivo's result visualizations – charts, word clouds, models – directly address this challenge. They act as bridges between the qualitative evidence and the audience's understanding. Showing a word cloud to community partners can provide an immediate sense of the main concerns of participants without requiring them to read through pages of quotes. The visual impact of seeing keywords in large bold letters can resonate more quickly than just stating "employment and health are common themes". Likewise, the bar chart of theme frequencies and the concept map offers talking points that makes the presentation of results more engaging and clearer. NVivo's visualization tools can improve the uptake of research findings, as they cater to visual learning preferences and can summarize complex data efficiently.

Using NVivo also has benefits for the interpretative phase of the research. By having all data and coding centralized, we could easily cross-check interpretations. If a surprising pattern emerged (for example, an unexpected cluster of participants linking two ideas), we could click on the visualization (in NVivo, many charts and models allow direct clicking through to the underlying data) to see the actual excerpts behind it. This can ensure the discussion of results remained grounded. It also can help in maintaining context – one of the criticisms of data visualization in qualitative work is the risk of oversimplification. This can be mitigated by using NVivo's capability to attach annotations and memos to visual outputs. For instance, when presenting the word cloud, this can be accompanied with quotes for the top terms to preserve the original voices. NVivo makes it easy to pull those illustrative quotes directly from the nodes associated with each theme.

In discussing NVivo's role, it's important to acknowledge practical limitations we encountered. Learning to effectively use the software required an upfront investment of time – setting up the project, creating a coding schema, and learning the visualization functions. This is consistent with reports that NVivo is not intuitive for new users and often demands training. This is managed by consulting NVivo's help resources and starting with NVivo's sample project for practice. Another consideration is that while NVivo's built-in visuals are great for analysis and internal use, they may need polishing for publication or formal presentations. The bar charts and models, for example, are exported and then slightly refined (increasing font sizes, adjusting colours). Experienced researchers often export NVivo visuals to software like PowerPoint or Adobe Illustrator for final touch-ups. This is not a flaw per se, but users should be aware that NVivo's focus is on analysis; presentation-ready graphics might require additional formatting. Despite these points, the time invested in learning NVivo was recompensed by the efficiency and clarity it brought to our project.

Had we conducted this qualitative analysis without NVivo, it would have been considerably more cumbersome to achieve the same depth. Manual coding of dozens of interviews would risk errors and make it difficult to reorganize themes dynamically. Creating visualizations like concept maps or maintaining counts of themes manually would be prone to mistakes. NVivo essentially acted as an analyst's assistant – handling data management tasks swiftly and accurately, so that we could focus on interpreting what the data meant. It is worth noting, however, that the researcher's critical thinking remains the driver of analysis. NVivo did not tell us what the themes are or why patterns exist; it enabled us to systematically arrive at those insights ourselves. This reflects the consensus in methodology literature that CAQDAS tools support but do not replace analytical judgement. The meaningful explanations (for example, why education links to income, or how policy affects outcomes) comes from our understanding and theoretical grounding, enriched by NVivo's efficient data handling.

In summary, the use of NVivo in research increases the analytical quality and helps in effectively presenting complex qualitative findings. The thematic maps and visual outputs makes analysis more transparent and communicable (the story in the data can be seen and not just read). These advantages align with broader observations that NVivo and similar software, when used thoughtfully, can raise the standard of qualitative research reporting. Nonetheless, the advice is to approach NVivo as a powerful toolkit – one that requires methodological care in its use – rather than a push-button solution. As with any tool, its value is maximized when combined with the researcher's expertise and critical insight.

6. Conclusions

The exploration of NVivo's application in qualitative data analysis demonstrates that it is a valuable resource for enhancing both the analytical rigor and the presentation of findings in scientific research. NVivo's advanced tools for data organization, thematic coding, querying, and visualization enable researchers in social and economic sciences to handle complex qualitative datasets with greater efficiency and depth. By leveraging NVivo, analysis that once might have taken months of manual work can be completed more systematically – yielding results that are not only robust but also easier to verify and update as new data comes in. The software contributes to making qualitative analysis more transparent and auditable, as every code, link, and conclusion can be traced back to source data.

Crucially, NVivo's visualization capabilities (charts, models, word clouds, etc.) support the interpretation and communication of research findings in ways that traditional text-based reports often cannot. They bridge the gap between rich qualitative insights and clear storytelling: helping highlight key themes at a glance, illustrating relationships between ideas, and engaging diverse audiences. A well-crafted word cloud or concept map can distill complex narratives into an accessible visual form, sparking conversation and understanding among stakeholders. This resonates with recent perspectives that data visualization in qualitative research is more than just aesthetic – it is a means of translating knowledge for broader impact. NVivo equips researchers with the tools to create such visuals within the analysis process itself, ensuring that visualization is integrated with, not separate from, analytic thinking.

Of course, using NVivo (or any CAQDAS) is not without challenges. Researchers must invest time in learning the software and be mindful to preserve the context and richness of the data when presenting visual summaries. However, as our discussion noted, these challenges can be managed through careful planning, training, and thoughtful use of the software's features. The benefits – in terms of enhanced insight and effective communication – tend to far outweigh the initial hurdles. It is also important to reiterate that NVivo aids but does not replace the researcher's role. Insightful qualitative analysis still depends on the researcher's critical interpretation, theoretical knowledge, and creativity in probing the data. NVivo simply provides a powerful platform to support this work, allowing researchers to go beyond surface-level analysis and uncover deeper stories within their data.

NVivo represents a significant step forward in the toolkit of qualitative researchers. By improving how data is organized, analyzed, and visualized, NVivo contributes to more rigorous and impactful qualitative research. For studies dealing with complex social and economic issues – where understanding nuance and conveying complexity are both essential – NVivo offers options that enhance analytical quality and enable the effective presentation of findings. As qualitative research continues to grow in prominence across disciplines, tools like NVivo will play an important role in ensuring that qualitative insights are systematically derived and powerfully communicated, ultimately bridging the gap between rich data and real-world decision-making.

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Constructing a Conceptual Model for the Modernization of a Small Family-Owned Enterprise

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Abstract. This study presents a conceptual model for the modernization of a small family winery, substantiated through a single case study. In contrast to linear approaches focused primarily on investment, the model demonstrates that sustainable development is achieved through the synchronous development of interrelated elements — or "nodes": technological, cognitive, and capital. Based on interviews with founders, analysis of financial statements, and a survey of several small wineries, systemic barriers hindering the development of the majority of small producers are identified. The key conclusion emphasizes the need for institutional support for small wineries through the implementation and expansion of the protected geographical indication system (IGP/DOP), which synchronizes the development of all model elements and ensures the market capitalization of quality.

Keywords: Family business, small wineries, technological modernization, conceptual model, knowledge management, economic sustainability, IGP, Moldova.

1. Introduction

Small family wineries play an important role in preserving the ethno-cultural landscape and constitute a significant element of the agricultural economy of the Republic of Moldova [42; 18]. Their importance is confirmed by official statistics: according to the National Bureau of Statistics [42], in 2024, small agricultural producers accounted for 63.4% of the gross grape harvest and 77% of the country's vineyard area. Over the past decade, a new wave of family winemaking entrepreneurship focused on producing high-quality wines has emerged in the country [44]. However, the development of this segment faces a persistent contradiction: while declaring a commitment to quality and traditions, these enterprises, according to empirical data, chronically underinvest in technological renewal and lack the managerial competencies necessary for effective market capitalization [32; 31; 17].

Contemporary research emphasizes that for small and medium-sized enterprises (SMEs), what becomes critically important is not merely possessing knowledge, but systematically managing it – its identification, preservation, transfer, and application [16; 12]. For family businesses, this task is complicated by the need to transfer informal, "tacit" knowledge between generations [13; 15]. Without formalized processes, accumulated experience risks being lost upon generational succession or the departure of a key employee [1].

Empirical data collected through an in-depth interview with the founders of the small family winery KaraGani Winery (September 2025) and a subsequent survey of 14 small farms

revealed a paradox: 100% of respondents cited lack of financial resources as the main obstacle to development. However, the successful case of KaraGani Winery demonstrates that access to grants alone is insufficient. A key role was played by the family's ability to institutionalize its knowledge – transforming oral rules into reproducible technological protocols, formalizing quality control procedures, and, ultimately, "packaging" unique experience into a brand eligible to use the protected geographical indication, recognized internationally through the IGP system [5; 14; 45]. This example, however, should not be considered typical; it represents more of an exception, demonstrating the development potential achievable through the synchronization of key factors.

The question arises: how can a small family winery synchronize investments in technology with the development of its ability to manage accumulated knowledge in order to achieve sustainable economic results? Approaches that reduce development to the sequence "investment → technology → quality → profit" [31] do not account for the specificity of small family businesses, where processes of knowledge management and intergenerational knowledge transfer play a critical role [16; 13]. As Meyer notes, any performance indicators degrade over time, and this problem is particularly acute in complex systems where non-financial indicators are difficult to aggregate [37].

The aim of this study is to construct and empirically substantiate a conceptual model for the modernization of a small family winery. This model views sustainable development as the result of the synchronous reinforcement of three interdependent basic elements – "nodes": technological, cognitive, and capital. Nodes are understood as key factors of production which, like points of support, must develop in a coordinated manner.

The scientific novelty of the research lies in the development of a conceptual modernization model which, unlike investment-oriented approaches, considers the sustainable development of a small family enterprise as the result of the synchronous reinforcement of three interconnected nodes. Novelty also lies in the interpretation of the system of protected geographical indications (IGP) as a dual institutional bridge, performing not only a market function but also a cognitive-disciplining one, stimulating the formalization of tacit family knowledge.

The key hypothesis is that a gap or asynchrony in the development of any node of the model blocks the enterprise's development, trapping it in one of several typical "traps" (for example, the "tradition trap" – possessing tacit knowledge but lacking modern technologies and the competencies to master them). The institutional mechanism IGP/DOP can function as a "bridge", converting modernization potential into market value [29; 14], while simultaneously acting as a disciplining factor, stimulating the formalization of internal processes [23]. The concept of strategic alignment, developed within enterprise architecture theory, confirms the necessity of synchronizing various subsystems to achieve sustainable development [36].

2. Theoretical Framework and Literature Review

This study draws upon three interrelated streams of literature: the economics of family business, theories of knowledge management in SMEs, and the theory of technological modernization. The synthesis of these streams provides the foundation for the conceptual modernization model proposed herein.

The primary asset of family wineries, which constitute the vast majority of producers in the global wine sector [4; 8], is the tacit knowledge accumulated over generations – an understanding of terroir, the nuances of technological processes, and the secrets of blending [1; 2; 23]. García et al. emphasize that heritage in family wineries serves as an active resource, shaping brand identity and competitive strategy [7]. However, this resource simultaneously

constitutes a source of vulnerability: research indicates that small family enterprises frequently encounter challenges related to knowledge continuity [12]. Tacit knowledge, if not formalized, risks being lost during generational succession [13; 15]. Consequently, a need arises to develop a set of processes enabling the family not only to preserve but also to augment its experience. In our model, this set of processes is termed the **Cognitive Node**. To analyze this node, we employ the process model of knowledge management [12; 13; 14], which encompasses knowledge identification through experimentation and external contacts, and its codification through documentation – exemplified by the Antinori family's experience of transmitting winemaking expertise across 700 years to subsequent generations [23].

A critical element in the codification and application of knowledge is the system of management accounting and control. This can be viewed as the formalization of the financial aspects of tacit knowledge – understanding cost structures, the profitability of sales channels, and investment efficiency. As Breslavtseva and Sverchkova emphasize, for small enterprises, management accounting is not merely an option but an essential survival tool, enabling the assessment of the true financial position, the identification of underutilized resources, and informed decision-making [32].

For "tacit knowledge" to be transformed into a marketable product, two other components of the model are necessary: the material base and the financial resources for its creation. This leads us to conceptualize the enterprise as a system of three interrelated elements (nodes). Jeffrey Lamy, synthesizing practical experience in winemaking, demonstrates that creating a successful winery requires the simultaneous management of craftsmanship, marketing, and capital [17]. The **Capital Node** in our model represents the combination of financial resources and the managerial competencies required for their effective allocation. The **Technological Node** comprises the material base (equipment, tanks, bottling lines) that enables the formalization and standardization of production processes, thereby ensuring quality consistency [31]. The choice of technology is inextricably linked to the cognitive processes of goal-setting and planning, determining not only investment efficiency but also the requirements for personnel qualifications and knowledge formalization [30].

The synchronous development of the three nodes does not guarantee market success if the product's quality remains opaque to the consumer. An institutional mechanism is required to convert internal efforts into market value. One such mechanism is provided by geographical indication (GI) system, which reduce information asymmetry and generate credible quality signals [24, 25, 42, 43]. Research shows that the presence of a GI can increase producers' incomes and their willingness to invest in quality, acting not only as a signal to consumers but also as a coordination tool within the value chain [26; 27]. For small producers, GIs function as an "institutional elevator" (a term used by Menapace and Moschini [25]), enabling them to compete with larger players on the basis of authenticity and uniqueness. In the Republic of Moldova, the regulatory foundation for GIs is Technical Regulation No. 356/2015 [22]. However, the costs of compliance often remain a critical barrier for small producers [29].

In our model, IGP (Indicație Geografică Protejată) acts as a dual "institutional bridge." On the one hand, it performs an external, market function: it sets standards and requirements for the Technological Node and converts certified quality into market value (a price premium). On the other hand, it performs an internal, cognitive function: the requirements of IGP stimulate the formalization of knowledge – compelling the producer to document processes, maintain records, and standardize operations. It is important to emphasize that IGP fulfills this function only when the producer possesses sufficient resources and motivation to undergo certification. However, where certification has been achieved, it transforms tacit family knowledge into an explicit, reproducible, and controllable asset [23].

Thus, the synthesis of theories of family business, knowledge management, and institutional economics leads us to construct a conceptual model for the sustainability of small family wineries, in which development is possible only through the synchronous reinforcement of the three nodes – technological, cognitive, and capital – unified by the institutional bridge of IGP.

3. Research Methodology

The research design constitutes a qualitative study with elements of quantitative analysis. This approach allows for combining the depth of analysis of a single successful case with the possibility of preliminary generalization through a survey of a limited sample [38].

Qualitative component. An in-depth case study [40] was conducted based on the small family winery KaraGani Winery (Vulcănești, ATU Gagauzia). The primary data collection method was a semi-structured interview with both founders of the enterprise (duration: 2 hours 40 minutes), conducted on September 9, 2025. The interview aimed to reconstruct the history of the farm's development, identify key investment decisions, sources of financing, changes in technological processes, and knowledge management practices. An additional source of information was the analysis of internal documentation provided by the respondents: financial statements for 2023–2024, grant applications and reports, and conformity certificates, including the right to use the protected geographical indication IGP "Valul lui Traian" (Oficiul Național al Vici și Vinului, nr. 36AV of August 21, 2019) [45].

Quantitative component. In January–February 2026, a survey of small family winemaking farms was conducted. Respondents were selected using the snowball sampling method: initial contacts were established through industry associations and the personal networks of the founders of KaraGani, who subsequently recommended other producers. All participants were informed of the research objectives and provided informed consent for the processing and publication of anonymized data. The inclusion criterion was operation as a family enterprise with a production volume characteristic of small farms (predominantly up to 10,000 liters per year, confirmed by 93% of respondents). This approach yielded a sample of 14 farms, located primarily in the southern region of the Republic of Moldova, which introduces a risk of systematic bias. This limitation is taken into account when interpreting the results.

The questionnaire included closed-ended questions concerning production structure, experience with grants, and certification, as well as open-ended questions about perceived barriers to development. The sample is not representative of the entire population of small wineries in Moldova; however, it enables the identification of persistent patterns and the formulation of hypotheses for further research.

To verify the obtained data and broaden the research context, an official request was submitted to the National Office of Vine and Wine (NOVW) for statistics on producers certified to produce IGP wines. The response received (February 2026) contains a complete list of such producers with their years of registration, allowing for a comparison of the survey results with industry-wide dynamics.

Analytical methods. Interview processing was carried out using thematic analysis [41]: recordings were transcribed, coded, and key themes corresponding to the model's nodes were identified. Quantitative survey data were processed using descriptive statistics (calculation of proportions and distributions). Open-ended survey questions were analyzed thematically: responses were grouped into meaningful categories (e.g., "certification cost," "procedural complexity"), and the frequency of mentions for each category was calculated.

Cross-analysis was conducted by comparing respondents' answers with the patterns identified in the case study. For each farm, an assessment was made of whether it fell into situations analogous to the "traps" identified in the model:

- lack of financing despite possessing knowledge (well-developed cognitive node, underdeveloped capital node);
- receipt of grants despite weak accounting and marketing practices (well-developed capital node, lagging cognitive node);
- non-utilization of IGP despite producing a quality product (existing potential, absence of institutional capitalization).

This comparison provided preliminary confirmation of the conceptual propositions of the model on empirical material, acknowledging the limitations of the sample size.

4. Research Results: The KaraGani Winery Case Study

The evolution of KaraGani Winery (vineyard area: 7 hectares) allows us to trace how each key activity progressively developed particular nodes of the model. Until 2013, the enterprise relied exclusively on manual labor and empirical control of vinification, which ensured the accumulation of tacit family knowledge.

A turning point came in 2013 with the receipt of a grant from the Government of Japan (JNPGA) amounting to €60,000 (co-financing conditions: 80/20). This enabled the acquisition of a set of technological equipment (destemmer-crusher, membrane press), ensuring fraction separation and temperature control - a transition to controlled technological processes (the technological node). Between 2017 and 2021, a series of grants (USAID, SARD, the Executive Committee of Gagauzia, SLPA, ODA), totaling over 1.8 million lei, funded the acquisition of aging equipment (barriques), solar panels, infrastructure elements for enotourism, and backup power equipment.

An interview with the founders, conducted on September 9, 2025, reveals that modernization did not reject traditional knowledge but rather formalized and enhanced it. This process is most vividly illustrated by three technological decisions.

Example 1: Fraction separation. The family's traditional empirical rule stated: "never mix free-run juice with press fractions." The acquisition of a five-stage pneumatic press allowed this rule to be implemented technically: the press is set to select only fractions at a pressure not exceeding 0.2 bar. Technology did not abolish tradition but translated it from the realm of "sensation" into the realm of a reproducible standard.

Example 2: Oxidation control. Family practice included an empirical taboo against introducing baker's yeast into the must, explained by the need to avoid undesirable fermentation. During modernization, this rule was reinterpreted and replaced by creating an inert CO₂ environment at all stages of processing—from crushing to aging. The traditional prescription received scientific justification and technical implementation.

Example 3: Malolactic fermentation. Entering international markets required bringing wines up to premium standards. The introduction of bacterial cultures for malolactic fermentation made it possible to reduce the high titratable acidity of red wines from 8 to 5.5 units, significantly soften the tannic structure, and produce a product competitive in European competitions.

In 2019, KaraGani Winery, as one of the first small enterprises in the IGP region "Valul lui Traian" (Moldova), obtained the right to use the geographical indication for varietal wines, particularly the high-quality local variety Fetească Neagră [45]. According to the founders, this decision was strategic, driven by the aspiration to move beyond the tourist flow, work with restaurants, and participate in international exhibitions on an equal footing with European producers. The IGP status was perceived not as a bureaucratic burden, but as recognition that

the wine embodies the uniqueness of place and territory. The histories of renowned wine houses, such as Antinori, confirm that the ability to formalize and transmit knowledge across generations underpins long-term success [23].

The analysis of the winery's cognitive evolution, reconstructed from interview materials, allows us to detail the transition from informal family practices to documented procedures. The main drivers of this transition were: participation in NOVW seminars and contacts with equipment manufacturers; the transformation of empirical rules into standard protocols and the implementation of regular laboratory controls; and the involvement of children in production processes and the consulting of colleagues. The culmination of this process was the creation of the premium wine line "CIOTRA" and successful IGP certification.

The dynamics of financial indicators for 2023–2024, presented in Table 1, demonstrate the business's increased resilience to external shocks (in this case, the 2024 crop failure). Net profit decreased by 45% (from 86,368 to 47,395 lei); however, return on sales declined only slightly - from 7.83% to 6.01%. The relatively low level of profitability is explained by the active investment phase of development (equipment acquisition, certification), characteristic of small enterprises at the scaling stage.

The key factor allowing the volume loss to be offset was the increase in the average sales price from 52.9 lei/l in 2023 to 82.1 lei/l in 2024, i.e., by 55.2%. To assess the extent to which this increase was due to reputational factors (IGP status, international awards) rather than general market conditions, we consulted data from the National Bureau of Statistics [42]. According to Table 5.8 of the Statistical Yearbook, the producer price index for grapes in 2024 was 137.2% relative to 2023, corresponding to an average industry-wide price increase of 37.2% [42].

Table 1. Key performance indicators of KaraGani winery (2023-2024)

KEY PERFORMANCE INDICATORS			
INDICATOR	2023	2024	CHANGE
PRODUCTION VOLUME, LITERS	20 850	9 600	▼ 54%
REVENUE, LEI	1 102 742	788 253	▼ 29%
NET PROFIT, LEI	86 368	47 395	▼ 45%
AVERAGE PRICE, LEI/L	52,9	82,1	▲ 55,2%
RETURN ON SALES, %	7,83%	6,01%	▼ 1,82 p.p.

Source: Internal financial records of KaraGani Winery

The ability to market a substantially smaller harvest at a significantly higher price enabled the enterprise not only to avoid losses but also to maintain profitability at a level close to that of the pre-crisis period.

5. Survey Results of Small Wineries

To verify the patterns identified in the case study, a survey of 14 small family farms in the southern region of Moldova was conducted in January–February 2026. Analysis of the obtained data allows us to characterize the state of the three nodes of the model within the studied sample and identify systemic barriers to development.

General characteristics of the sample. Among the respondents, farms with extensive winemaking experience predominate: 65% have been operating for over 15 years, and a further

14% for 10 to 15 years. At the same time, 93% produce up to 10,000 liters of wine per year, corresponding to the status of micro-enterprises. The assortment of the majority (79%) is limited to 2–3 wine varieties, and only 14% offer 5–10 items, including wines from indigenous grape varieties.

Cognitive node. The vast majority of respondents (86%) recognize quality as the main success factor, directly influencing sales, tourist attractiveness, and awards. However, this declared commitment to quality is not supported by institutional formalization: 64% of farms do not certify each batch of production, relying on traditional methods and customer feedback. Only 21% undergo mandatory certification for each batch, and a further 14% certify only new products when the recipe changes.

Technological node. This node is characterized by significant backwardness: 71% of respondents work "the old-fashioned way," without implementing new technologies over the past 10 years. Only 29% have acquired modern equipment (presses or temperature-controlled tanks). Moreover, 57% are ready to modernize only on the condition of receiving a grant, which creates a risk of a "capitalization gap." A further 29% do not yet plan changes, considering traditional methods sufficient, and only 7% are oriented towards digitalization (vineyard sensors, online sales).

Capital node. This node demonstrates a high dependence on external financing with limited access to it. Experience in receiving grants is held by 29% of farms; 71% have never received either grants or loans, financing development exclusively from their own funds. None of the respondents have used credit resources (100%). At the same time, all respondents (100%) cited lack of finance as the main barrier to implementing new technologies.

Analysis of the open-ended questions revealed the main obstacles to obtaining IGP status, which explain why 64% of farms do not certify their production despite recognizing the importance of quality. The high cost of certification and analyses was noted by 73% of respondents, and the complexity and bureaucratization of procedures by 64%. More than half (55%) indicated a lack of information about the certification process, and 45% are unsure of the economic return on investment.

To verify the obtained conclusions at the industry level, an official request was sent to the National Office of Vine and Wine. The data received (February 2026) contain a complete list of producers certified to produce wines with a protected geographical indication (IGP), including their years of registration. Figure 1 presents the dynamics of this process.

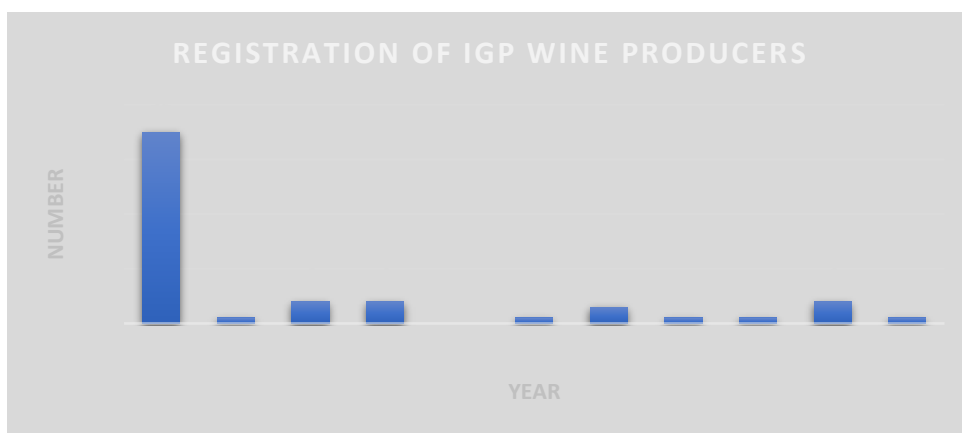


Fig. 1. Dynamics of IGP wine producer registration in the Republic of Moldova

The graph clearly shows two stages in the institutional development of the IGP system in Moldova. The first stage (2016) is characterized by a mass entry of producers - in a single year, 35 enterprises received IGP status, accounting for 66.7% of all those certified by 2026. The second stage (2017–2026) is marked by isolated additions: on average, 1-4 new producers per year, with no growth at all in 2020.

6. Conceptual Model of Modernization

The analysis of the KaraGani Winery case study and the survey data from small wineries allows us to formalize a model for the sustainable development of a small family winery – the "MODERNIZATION TRIAD" (Fig. 2). The model proceeds from a simple yet often overlooked thesis: the sustainability of an enterprise depends not on a single resource, but on the synchrony of all, in this case, three interconnected nodes:

- **TECHNOLOGICAL NODE** – the material and technical base (equipment, process control, quality consistency);
- **COGNITIVE NODE** – the knowledge management system (identification and codification of tacit knowledge, experience sharing, continuity);
- **CAPITAL NODE** – financial resources and managerial competencies (access to grants, management accounting, profitability).

Nodes are understood as key factors of production and development; the lagging of any one of them renders the system unstable. The institutional mechanism for synchronization is the system of protected geographical indications (IGP/DOP), performing the function of a dual bridge. This structure resonates with the ideas of strategic alignment developed within enterprise architecture theory, where the coordinated development of various subsystems is considered a necessary condition for effectiveness [36].

The structure of the model is represented by a diagram of elements reflecting various aspects of the functioning of a family winemaking enterprise, presented by three basic nodes and the IGP institutional bridge block. Numbers 1–6 on the bidirectional arrows between the nodes indicate inter-nodal influences:

- ① — knowledge influences the choice of technologies and equipment;
- ② — technology enables the formalization and standardization of tacit knowledge;
- ③ — financial resources enable technological renewal;
- ④ — effective technologies increase profitability;
- ⑤ — investments are directed towards staff training and development;
- ⑥ — managerial competencies enhance the efficiency of capital utilization.

Bidirectional dashed arrows between each node and the "IGP Institutional Bridge" block reflect mutual influence: the level of node development determines the possibility of obtaining certification (technologies must meet standards, knowledge must be formalized, capital must allow covering the procedures); in turn, IGP influences the nodes by setting standards (technological node), stimulating knowledge formalization (cognitive node), and converting certified quality into market value (capital node).

The broad arrow leads to the ultimate result of the synchronous development of all three nodes through the **IGP INSTITUTIONAL BRIDGE** - sustainable development, understood as the enterprise's ability to maintain profitability and reputation under conditions of external shocks (crop failure, market volatility).

MODERNIZATION TRIAD

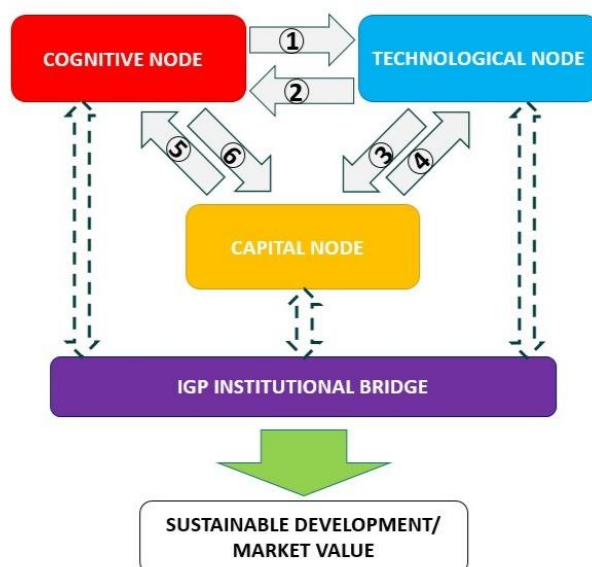


Fig. 2. Conceptual model for the modernization of a small winery

The institutional mechanism capable of synchronizing the development of all three nodes and "extracting" the enterprise from the described traps is the system of protected geographical indications (IGP/DOP). Within the framework of the model, IGP is interpreted as **a dual institutional bridge**:

- **the external bridge** – sets standards and requirements for the technological node and converts certified quality into market value, providing a price premium.
- **the internal bridge** – certification requirements compel the producer to formalize knowledge: documenting processes, standardizing operations, thereby creating a foundation for intergenerational knowledge transfer.

It is important to emphasize that IGP performs this function only under the condition that access barriers are overcome: where certification has been achieved, it triggers the mechanism of node synchronization, transforming family experience into a market asset.

While the KaraGani Winery case demonstrates that the synchronous development of the three nodes combined with institutional capitalization through IGP ensures sustainability even in unfavorable years, the survey data from other wineries record the opposite situation: asynchrony or a gap in the interaction of the nodes keeps enterprises in one of three typical "traps," each of which has empirical confirmation (Table 2).

Thus, the "MODERNIZATION TRIAD" describes a model for the sustainable development of a small family winery as a dynamic process of synchronous reinforcement of the three nodes—technological, cognitive, and capital—united by the institutional bridge of IGP, which standardizes production, formalizes knowledge, and capitalizes quality into market success.

Table 2. Typology of traps (GAPS) in the modernization triad

TYPOLOGY OF MODERNIZATION TRAPS		
TRAP/GAP	CHARACTERISTICS	EMPIRICAL BASIS
"TRADITION TRAP"	Unstable quality – inability to scale	71% of the sample work "the old-fashioned way"
"CAPITALIZATION GAP"	Risks of relying solely on external financing	57% of respondents are ready to modernize only if they receive a grant
"IGP BARRIER"	Lack of institutional recognition blocks access to price premium	64% do not certify their products

Source: Survey of small wineries (n=14)

7. Discussion of Results and Conclusyiona

This study contributes to the discourse on pathways for modernizing small family agricultural enterprises. The proposed "triad" model advances resource-based approach ideas within the wine sector context. While previous research often focused on individual factors—technological renewal [31; 13], knowledge management [16; 12], or financial mechanisms [32; 17]—our model demonstrates their systemic interrelationship, showing that each of these factors yields effects only in conjunction with the other two.

The key theoretical conclusion is that the sustainability of a small family enterprise is ensured not by the maximal development of a single resource, but by the synchronization of the three nodes. Empirical evidence confirms: the presence of grants (capital) without formalized knowledge (cognitive node) leads to a "capitalization gap"; rich traditions without technologies reinforce the "tradition trap." Thus, we refine Lamy's thesis on the necessity of simultaneously managing craftsmanship, marketing, and capital [17], and also develop the ideas of De Massis et al. on the specificity of innovation in family firms [5], concretizing the synchronization mechanisms for small winemaking enterprises. Our approach also resonates with the concept of strategic alignment developed within enterprise architecture theory, where the coordinated development of various subsystems is considered a necessary condition for effectiveness [36].

The second significant finding concerns the dual role of IGP. In the literature, geographical indications have traditionally been viewed as a marketing tool and a means of protection against counterfeiting [24; 25; 42]. Our research shows that for family wineries, the process of preparing for IGP/DOP certification performs an equally important internal cognitive function, compelling the formalization of tacit knowledge and creating a foundation for intergenerational knowledge transfer. IGP acts not merely as a certificate, but as a managerial disciplining mechanism, opening a new line of inquiry: the study of geographical indication systems as knowledge management tools in small businesses. The historical experience of leading wine houses, such as Antinori, confirms that the ability to formalize and transmit knowledge across generations underpins long-term success [23].

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Information and Telecommunication Technologies as the Basis of Modern Cyber Security

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Abstract. The article analyzes the role and place of information and telecommunication technologies (ITT) in the structure of modern cybersecurity systems. The evolution of architectural approaches is studied: from classical perimeter defense to the Zero Trust model. Key components of ITT, such as cloud computing, artificial intelligence, cryptographic protocols, and zero trust network architectures, are analysed. Particular attention is paid to the transformation of protection methods under the influence of the growing complexity of cyber threats. An analysis of the integration of artificial intelligence and machine learning as an intellectual core for analysing large arrays of security events in real time is performed. The use of blockchain technology to ensure the immutability of audit logs is considered. Based on the analysis of major cyberattacks during 2022–2025, critical technical errors are identified, and ways to strengthen cyber resilience through the implementation of EDR/XDR systems and response automation are proposed.

Keywords: cyber defense, information and telecommunication technologies, artificial intelligence, machine learning, Zero Trust, blockchain, information security, monitoring.

1. Introduction

Today, the world is undergoing a phase of total digitalisation, characterised by the penetration of information and telecommunication technologies (ITT) into all areas of life: from public services and medicine to critical infrastructure management. The concepts of the ‘Smart City’ and the digital economy are based on the continuous exchange of data. However, this global interdependence creates unprecedented challenges for national and international security. Cyber defence is no longer an optional extra but has become an integral part of the architecture of any information system.

Global digitalisation is an irreversible process that has brought enormous benefits to humanity, but at the same time has made it vulnerable. New challenges require a transition from ‘patching vulnerabilities’ to building resilient systems where protection is integrated into the IT architecture itself at the design level (Security by Design).

Global digitalisation has led to exponential growth in the number of connected devices. The introduction of Internet of Things (IoT) and 5G technologies means that the entry point for a hacker can now be not only a company's server, but also a ‘smart’ temperature sensor, surveillance camera or medical implant. Each new node in the network expands the overall ‘attack surface’ that needs to be protected.

The modern challenges lie in the fact that cyber attacks are no longer limited to virtual space. The digitisation of critical infrastructure (power grids, water supply systems, transport) means that a successful intrusion into an IT system can lead to real man-made disasters. Cyber weapons have become a tool of geopolitical influence, as clearly demonstrated by the events of 2022–2025.

2. Research objectives and methods

The aim of the article is a comprehensive study of the role of information and telecommunication technologies in forming resilient cyber defense systems, as well as an analysis of the effectiveness of integrating artificial intelligence, Zero Trust architecture, and blockchain technology to counter modern cyber threats in the context of global digitalization.

To achieve the set goal, a set of scientific methods was used to ensure objectivity and depth of analysis:

1). System analysis method: used to study ITT as an integral structure, where each component (network, endpoint, cloud) plays a specific role in the overall security system.

2). Comparative-typological method: used to compare traditional perimeter protection models with modern Zero Trust architectures, as well as to analyse different data formats (IDMEF, JSON, CEF).

3). Statistical and descriptive methods: used to analyse large-scale cyberattacks in the period 2022–2025 to identify patterns of technical errors and their impact on the scale of incidents.

4). Process modelling: used to describe the mechanisms of the intelligent core based on machine learning algorithms (e.g., Random Forest) in the process of detecting anomalies in network traffic.

5). Deduction and generalisation method: allowed us to formulate a comprehensive concept for the promising development of autonomous cyber defence systems based on the studied technological trends (blockchain, AI, 5G).

3. Presentation of the main research material

Traditional defence methods based on human analysis face the challenge of speed. Malicious actors are increasingly using artificial intelligence to automatically search for vulnerabilities in software code, generate personalised phishing (Deepfakes) and create viruses that change their structure (polymorphic code) during propagation.

There are issues of trust and digital transparency, as in a globalised world, data is often stored on servers in different countries (cloud computing). This creates a challenge for legal and technical control to ensure data security. This stimulates the development of confidential computing technologies and the localisation of critical network segments.

Given the rapid digitalisation of society, the human factor plays an important role in the digital environment, which is the weakest link. Digitalisation is outpacing the level of cyber hygiene among the population. It makes services as accessible as possible: one-click payment, biometrics, cloud storage.

The problem is that users get used to comfort, perceiving digital services as ‘magic’ that works by itself. This lulls them into a false sense of security. For example, a person may use one easy password for all services in order to avoid unnecessary inconvenience [7].

Previously, phishing emails were easy to spot due to errors in the text. Today, attackers use neural networks. Hackers imitate the voice of a boss or the video image of a relative to trick a person into transferring money or providing access to the network. Artificial intelligence analyses the victim's social networks and generates messages that a person is 90% likely to believe. The cyber hygiene of the population simply cannot keep up with such a rapid pace of manipulation.

Company employees often use personal messengers or cloud services for work documents because it is ‘faster.’ They do not realise that they are removing corporate data from the protection of SIEM or DLP systems. Here, the digitalisation of processes (the transition to the cloud) has outpaced the understanding of the risks of data leakage.

According to international reports (including IBM and Verizon), between 82% and 90% of all successful cyber attacks start with the ‘human factor’ [6]. The average time it takes to train a user in new security rules is 6-12 months, while new types of attacks appear every week.

Since it is impossible to teach 100% of the population perfect cyber hygiene, modern cyber protection shifts the responsibility to technologies, which include:

- Passwordless (passwordless login), i.e. replacing passwords with hardware keys (FIDO2) or biometrics so that the user cannot ‘accidentally’ give their password to a phisher;
- Zero Trust - the system does not trust the user even after login, constantly checking their actions for anomalies;
- automated sandboxes - checking all attachments in email with AI algorithms before the user has time to open them.

Thus, poor cyber hygiene is a link in the chain of modern cyber threats. Therefore, the architecture of modern information and telecommunications technologies must be based on the principle of ‘resilience to human error,’ where the protection system is capable of automatically neutralising the consequences of ill-considered user actions.

Modern cyber protection based on the CIA triad is important: confidentiality (protection against unauthorised access); integrity (protection against unauthorised data modification); availability (ensuring uninterrupted access to services). Information and telecommunications technologies ensure the technical implementation of this triad through the introduction of automated monitoring and access control systems.

An analysis of major cyberattacks in recent years shows that even the world's most powerful corporations are vulnerable due to basic technical miscalculations. Below is an analysis of the most high-profile incidents of the period 2022–2025.

Looking at the attack on MGM Resorts in 2023, which was one of the most high-profile attacks and paralysed hotels in Las Vegas for several weeks, it should be noted that the Scattered Spider group gained access to the internal network through a regular phone call to the IT help desk, posing as an employee [3]. The technical flaws in the attack were the lack of strict identity verification, i.e. the support service did not have a protocol for visual or cryptographic identity verification when resetting passwords. The account privileges were excessive. Once they gained access to a single account, the hackers were able to quickly elevate their privileges to Okta (Identity Provider) administrator level, giving them control over the entire infrastructure.

Another example of an attack that took place in 2023 was the MOVEit hack (2023) - a zero-day vulnerability that affected thousands of organisations around the world, including US government agencies and major banks [3].

Hackers exploited a critical SQL injection vulnerability in the MOVEit Transfer file transfer software. Analysing the mistakes that were made, it was a lack of proper protection when logging into the system. The software did not properly filter input data in SQL queries, allowing hackers to execute arbitrary commands in the database. Direct access to the databases was gained, allowing attackers not only to read but also to download huge amounts of confidential information.

Another example was the attack on Snowflake in 2024 due to a large-scale leak of customer data from the Snowflake cloud platform (including Ticketmaster and Santander Bank) [4]. Hackers stole data from Snowflake customer accounts using previously stolen credentials.

Technical errors include the lack of mandatory multi-factor authentication (MFA), meaning that many customer accounts were protected only by a login and password. In today's environment, this is considered a critical configuration error.

In addition, the long lifetime of session tokens meant that sessions did not end automatically, giving attackers time to download terabytes of data without re-authentication.

In 2025, there was a surge in attacks where AI-Driven Phishing generated perfect phishing messages based on open source intelligence (OSINT) [5]. The mistake was placing too much trust in traditional email filters. Old email protection systems look for known malicious links, but miss AI-generated emails that do not contain viruses, but only persuade the user to voluntarily transfer data.

Thus, the scale of attacks is usually determined not by the genius of hackers, but by three factors: human - staff unpreparedness for social engineering, weak identity management (IAM) - lack of MFA and the principle of least privilege, and lack of visibility - companies learn about breaches too late due to the lack of configured monitoring and event correlation (SIEM).

4. Conclusions

Thus, reliable cyber protection requires a technological transformation that will apply automated threat detection and neutralisation in automated systems with information and telecommunications technologies for data transmission and processing.

With millions of security events generated every second, the introduction of artificial intelligence and machine learning is a critical necessity. Only algorithms are capable of detecting complex anomalies and zero-day attacks in real time that remain invisible to humans.

Traditional protection is no longer effective. The transition to Zero Trust architecture minimises the risks associated with account compromise and internal threats through constant verification of each network entity, which is also an advantage of this zero trust concept.

The use of decentralized registries for storing audit logs solves the problem of 'trust in the administrator.' Blockchain guarantees the immutability of the evidence base, which is a key factor for successful investigation of cybercrimes (Digital Forensics). Despite the high technological sophistication of modern ITT, configuration errors and social engineering remain the main vulnerabilities. Effective cyber protection is only possible when advanced technologies (EDR/XDR/SIEM) are combined with ongoing staff training and strict adherence to security policies.

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Global Trends and National Realities in ESG Reporting

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Abstract. Environmental, Social, and Governance (ESG) reporting has emerged as a critical tool for organizations seeking to demonstrate their commitment to sustainable practices and social responsibility. As investor interest and regulatory pressures continue to rise, understanding the evolving trends and challenges in international ESG reporting has become essential. This research explores the global landscape of ESG reporting, examining the key trends, frameworks, and regulations shaping corporate disclosures. By analyzing the current state of ESG integration in the Republic of Moldova, this paper identifies the "implementation gap" between global mandates and national reporting capacities. Despite advances, challenges such as inconsistent data quality and the structural transition from fiscal-oriented to sustainability-oriented reporting persist. The study concludes that the successful integration of ESG reporting in Moldova is fundamentally contingent upon the transition from the fiscal-oriented National Accounting Standards (NAS) to the transparency-driven IFRS framework, as the latter provides the essential data architecture for credible sustainability disclosures.

Keywords: ESG Reporting, Sustainability, Global Standards, Reporting Frameworks

1. Introduction

Companies across industries now recognize the importance of aligning their operations with environmental, social, and governance (ESG) principles. Investing time, resources, and effort into embedding sustainability is a strategic requirement for accessing international capital markets; it's about redefining business models and seizing opportunities for growth and innovation. At its core, ESG reporting is the disclosure of environmental, social, and corporate governance data. This comprehensive approach allows companies to communicate their commitment to sustainability and responsible business practices to stakeholders, including investors, customers, and regulators. ESG reporting goes beyond financial metrics, providing insight into a company's broader impact on society and the environment. By disclosing ESG performance metrics, companies demonstrate their dedication to transparent and responsible business practices, fostering trust and credibility with stakeholders. Despite this global momentum, domestic investment in environmental protection remains significantly lower than European benchmarks. Both government and business spend too little on these purposes. In recent years, Moldova has allocated only 0.5% of GDP to environmental protection, while the EU average is 1.9%. [1, p.13] There are multiple reasons for under-investment, generally linked to financial constraints and the state of the Moldovan economy. Environmental protection is often sacrificed in favor of other political or economic priorities.

2. Methodology

This study adopts a qualitative, exploratory approach based on:

- Normative analysis: Reviewing EU Directives (CSRD/ESRS) and the Moldovan legislative framework (Environmental Strategy 2024-2030);

- Comparative benchmarking: Evaluating the reporting practices of national "Pioneering Entities" (MAIB S.A., Moldcell S.A., Purcari Wineries PLC) against ESRS standards;
- Diagnostic analysis: Investigating the implementation challenges of ESG reporting through a tiered approach, from regulatory inconsistencies to professional skill shortages;
- Gap analysis: Identifying the structural barriers in the transition from fiscal-oriented (NAS) to investor-oriented (IFRS/ESG) reporting.

3. Current trends in international ESG reporting

The year 2026 is positioned as a pivotal juncture in the European reporting timeline. Following the introduction of the "Omnibus I" package and the "Stop-the-Clock" Directive (Directive (EU) 2025/794), the EU has fundamentally recalibrated its implementation schedule to balance the urgent need for transparency with the necessity of maintaining corporate competitiveness [21]. The provisional agreement reached in December 2025 has significantly altered the size thresholds for mandatory reporting, focusing on entities with at least 1,000 employees and €450 million in annual net turnover [20, p.3].

Table 1. Recalibrated CSRD Implementation Timeline under the Omnibus I Package and Directive (EU) 2025/794

Reporting Category	New Size Thresholds (Omnibus I)	Initial Reporting Year	Report Publication Year
Wave 1 (NFRD Companies)	> 500 employees (historical)	2024	2025
Wave 2 (Large EU Undertakings)	> 1,000 employees & > €450M Turnover	2027	2028
Wave 3 (Non-EU Parent / Art 40a)	> €450M EU Group Turnover	2028	2029
Voluntary SMEs (VSME)	Below mandatory thresholds	Optional	Optional

Source: Prepared by the authors based on [20]

The "Stop-the-Clock" Directive effectively postpones existing reporting requirements for Wave 2 and Wave 3 entities by two years, providing a "transition year" in 2026 for these organizations to build the robust data-collection structures required for future compliance. Meanwhile, Wave 1 entities benefit from "Quick Fix" amendments adopted in July 2025, which allow them to maintain or even reduce the level of reporting applied in 2024 for their 2025 and 2026 reports, thereby reducing the immediate administrative burden during the phase-in period [20,p.1;5].

The evolution of ESG reporting has followed a gradual, tiered trajectory, with large companies leading the adoption process and small and medium-sized enterprises (SMEs) progressively following suit. Initially, ESG disclosure was largely voluntary and concentrated among large, publicly listed entities with strong exposure to international markets and investor scrutiny. These companies were the first to align with early frameworks such as the GRI, TCFD, or SASB, driven by reputational and regulatory incentives. The introduction of the EU Non-Financial Reporting Directive (NFRD), and more recently the Corporate Sustainability Reporting Directive (CSRD), marked a significant shift toward mandatory ESG disclosure. Under CSRD, large entities—including those already covered by NFRD—are required to

publish ESG reports aligned with the European Sustainability Reporting Standards (ESRS) starting from the 2024 financial year, with a phased extension to non-listed large companies and SMEs. Listed SMEs will become subject to mandatory reporting obligations from the 2026 financial year, with optional deferrals until 2028.

This phased implementation reflects both the growing importance of ESG transparency and the structural differences in reporting capacity across company sizes. While large entities generally possess the financial and human resources necessary to integrate ESG into their governance systems, SMEs face notable challenges—ranging from limited internal expertise and high compliance costs to difficulty accessing ESG-specific assurance services. Nevertheless, SMEs are increasingly impacted by indirect pressures via supply chains, investor expectations, and regulatory alignment, making ESG integration a strategic imperative across all company tiers.

Table 2. Timeline of ESG Reporting Expansion: Large Companies vs. SMEs
(EU, 2014–2028)

Year / Phase	Large Entities	Small and Medium-sized Enterprises (SMEs)
2014–2017	Voluntary ESG reporting, primarily by large listed companies	Minimal or negligible ESG reporting practices
2018	NFRD becomes effective – mandatory for large public-interest entities	SMEs not covered by NFRD
2021	CSRD proposed – extends obligations to all large companies	Upcoming applicability announced for listed SMEs
2024 (FY)	Mandatory reporting under CSRD and ESRS (reports published in 2025)	Not yet mandatory, but indirect pressures increase
2026 (FY)	Majority of large companies report under ESRS	Listed SMEs begin mandatory reporting under CSRD (reports in 2027)
2028 (FY)	Expanded ESG audit requirements introduced ("reasonable assurance")	Final deadline for listed SMEs; potential voluntary extension

Source: Prepared by the authors based on [11,12,13,14]

Although the CSRD Directive mandates sustainability reporting for approximately 50,000 companies within the European Union, recent data indicate that only a portion of these entities currently comply with the requirements. ESG reporting is predominantly observed among large companies, with approximately 82–90% of entities within the N100 category already disclosing non-financial information. However, surveys reveal that less than 5% of the companies targeted in the first phase of CSRD implementation are fully prepared to meet the new standards. This discrepancy highlights a significant gap between the legal obligation and the actual capacity for compliance, underscoring the need for concerted internal adaptation efforts and institutional support to ensure effective ESG reporting implementation at the European level [11].

The figure below presents the ESG reporting rates among N100 (top 100 companies by revenue in each country included in the survey) companies in Europe for the years 2022 and 2024, highlighting the progression in sustainability disclosure practices over time.

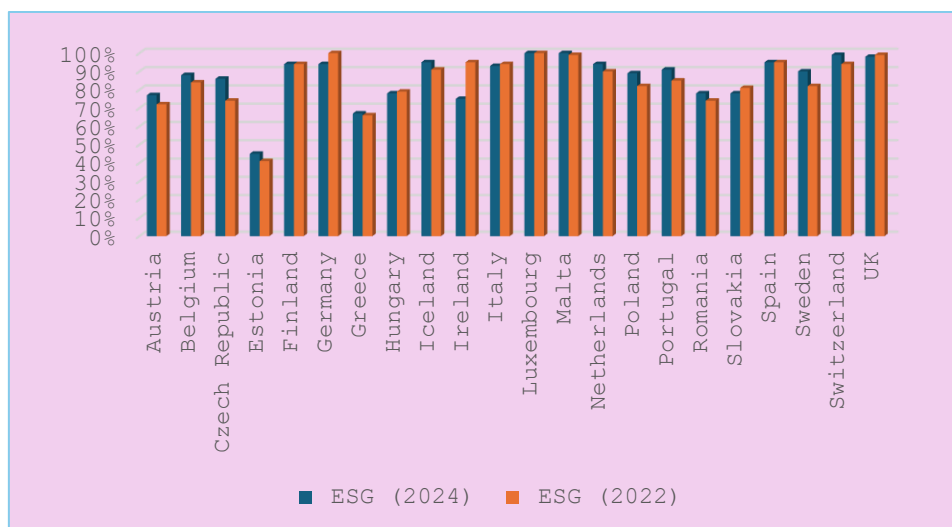


Figure 1. ESG Reporting Rates in Europe in 2022 and 2024 among N100 Companies (top 100 companies by revenue in each country included in the survey), Source: Prepared by the authors based on KPMG’s Survey of Sustainability Reporting 2024 [11]

The analysis of ESG reporting among the top 100 national companies in Europe reveals a clear trend toward the maturation and expansion of sustainability disclosure. Most European countries exhibit ESG reporting rates exceeding 75%, with some—such as Luxembourg and Malta—reaching full compliance (100%). This suggests a rapidly advancing alignment with European regulatory requirements, particularly the CSRD.

Western and Northern European countries—such as Germany, the Netherlands, Sweden, Switzerland, and the United Kingdom—are at the forefront of this process, consistently reporting figures close to or at 100%. These outcomes reflect not only regulatory compliance but also a strategic integration of sustainability within corporate business models.

By contrast, Eastern European countries such as Romania, Slovakia, and Estonia report comparatively lower levels of ESG disclosure. Nevertheless, these countries have demonstrated positive progress since 2022, indicating a gradual convergence toward Western standards. For instance, Romania’s ESG reporting rate increased from 74% to 78%, signaling both advancement and significant room for improvement.

This regional distribution underscores the persistence of an East–West gap in ESG maturity, shaped by factors such as regulatory infrastructure, corporate culture, investor pressure, and the degree of integration into international financial markets.

The evolution of ESG reporting increasingly relies on digital technologies and real-time data integration to enhance transparency, accuracy, and operational efficiency. Across Europe and globally, organizations are adopting advanced software solutions that automate data collection, analyze sustainability metrics, and facilitate compliance with regulatory frameworks such as the ESRS and CSRD, as well as international standards like the Global Reporting Initiative (GRI).

Specialized ESG reporting platforms, including Zoei ESG and Dcycle, provide integrated systems for real-time monitoring of environmental indicators, carbon footprint analysis, and automatic report generation, significantly reducing manual effort and improving data reliability [19].

Furthermore, cutting-edge tools such as ESG Reveal leverage large language models (LLMs) to extract structured data from diverse reports, enhancing the precision and efficiency of ESG disclosure analysis [18]. Empirical evidence underscores the importance of digitalization in overcoming key barriers to sustainable investment. A survey by BNP Paribas revealed that over 70% of investors perceive insufficient and inconsistent ESG data as major obstacles to green investments, highlighting the urgent need for digital solutions that ensure accurate and timely ESG reporting [16]. Moreover, artificial intelligence-driven models like Deep Search DocQA facilitate the analysis and interpretation of sustainability reports, offering actionable insights and alignment with global reporting standards [17].

These innovations empower companies to not only meet regulatory requirements but also to enhance their sustainability performance proactively.

While digitalization and mandatory CSRD compliance are accelerating in Western Europe, emerging markets like the Republic of Moldova face a different set of structural hurdles. The transition from a fiscal-driven accounting culture (NAS) to a transparency-driven ESG framework represents not just a technical change, but a systemic challenge, as explored in the following section.

4. Multidimensional barriers to ESG Reporting

Although ESG reporting has gained considerable prominence as a tool for promoting corporate accountability and sustainable development, its practical implementation continues to face substantial limitations. These challenges arise not only from the absence of a globally harmonized regulatory framework, but also from technical and structural inconsistencies that affect the quality, comparability, and reliability of disclosed information.

Moreover, variability in institutional capacity, especially between large corporations and SMEs, contributes to unequal levels of ESG integration and reporting maturity. In many cases, ESG disclosures remain fragmented, non-standardized, and insufficiently verified, thus limiting their effectiveness as instruments for informed decision-making by investors and stakeholders [11]. These challenges are categorized across different levels—normative, technical, procedural, analytical, perceptual, and structural—and are further illustrated in Fig. 2.

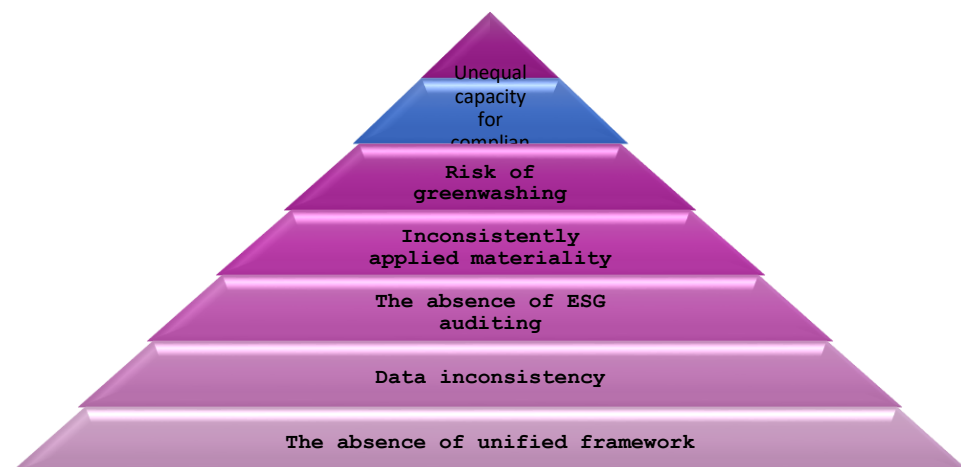


Figure 2. Gradual overview of ESG Reporting limitations
Source: Prepared by the authors, adapted from KPMG (2024) [11] and
IFRS Foundation (2024) [3].

To provide further clarification of these limitations, the following section presents detailed descriptions and illustrative examples corresponding to the challenges identified in Figure 2.

- **Lack of Universal Standardization/absence of unified framework (Basic Level – Normative/Regulatory).** One of the most common limitations lies in the absence of a globally unified ESG reporting framework, resulting in fragmented application of requirements depending on the region or industry.

Example: A multinational company may be required to comply with GRI standards in one jurisdiction, ESRS in the EU, and SASB in the US, complicating unified reporting.

- **Data Inconsistency and Quality (Technical Level – Operational).** ESG reporting frequently relies on self-declared data, without rigorous data collection methodologies or external audits. This compromises the comparability and credibility of the results [11,12].

Example: CO₂ emissions may be estimated differently by two companies within the same sector due to the lack of standardized measurement methods.

- **The absence of ESG auditing (Procedural Level – Governance).** A significant proportion of ESG reports are not subject to external audits or other forms of independent assurance, thereby reducing confidence in their content.

Example: Only approximately 54% of European companies that report ESG data request external verification [11].

- **Inconsistently applied materiality (Analytical Level – Strategic).** Companies often select ESG topics based on their own criteria, without rigorous analysis of the actual economic, social, or environmental impact.

Example: Some companies report charitable actions or social campaigns but avoid addressing major environmental risks within their supply chains.

- **Risk of Greenwashing (Perceptual Level – Reputational/Ethical).** Without clear standards and external verification, some entities may use ESG reporting for purely image-related purposes, portraying exaggerated or incomplete sustainability performance.

Example: An oil company may publish an ESG report emphasizing internal recycling efforts but omit crucial data concerning industrial pollution.

- **Unequal Capacity for Compliance (Structural Level – Institutional Development).** There is a significant gap between large companies, which have dedicated resources, and SMEs that often lack the tools, expertise, or know-how to implement complex ESG reporting [14].

Example: In Eastern Europe, many medium-sized companies lack internal ESG teams and specialized consultants.

The gradual presentation of ESG reporting limitations reveals that the obstacles are not solely technical or legal in nature but also involve issues related to governance, ethics, and institutional capacity. An effective approach to addressing these limitations requires not only the harmonization of standards but also the strengthening of organizational culture around sustainability.

The tiered limitations described above demonstrate that the obstacles to effective ESG integration are systemic. For an emerging economy like the Republic of Moldova, these global challenges are further amplified by local institutional voids, as explored in the subsequent analysis of the national regulatory context.

5. ESG integration in the national regulatory and economic context

While ESG reporting has gained momentum globally, its development at the national level remains uneven, particularly in emerging economies. In the case of Moldova, ESG practices are still at an early stage, shaped by limited regulatory pressure, low awareness among market participants, and a lack of standardized reporting infrastructure. However, recent alignment efforts with European Union sustainability regulations—especially within the broader context of Moldova’s EU integration agenda—have initiated a shift toward more structured environmental, social, and governance disclosure practices. This section explores the current ESG landscape within the country, analyzing legal developments, institutional readiness, reporting trends, and the main challenges faced by local entities in adopting ESG standards. It also considers the extent to which Moldova aligns with international best practices and what steps are needed to strengthen ESG reporting as a lever for sustainable economic and social development.

To facilitate the transition towards a sustainable economy, the Republic of Moldova has recently adopted a series of strategic policies that establish the foundational framework for national ESG integration. These governance trends signal a clear shift towards European alignment:

✓ **Environmental Strategy 2024–2030:** Approved in June 2024, this strategy targets a significant 70% reduction in net greenhouse gas (GHG) emissions by 2030 compared to 1990 levels. It focuses on cross-sectoral climate adaptation and pollution reduction, providing the 'Environmental' (E) targets that corporations will eventually need to report against [5].

To understand the scale of the reporting requirements facing national enterprises, it is essential to analyze the specific decarbonization targets set by the government. These targets, categorized by economic sector, represent the key performance indicators (KPIs) that will form the backbone of future environmental disclosures in Moldova as presented in Table 3.

Table 3. Sectoral GHG emission reduction targets by 2030 (Republic of Moldova)

Sector	GHG Emission Reduction Target (by 2030)
Energy	74% (Unconditional)
Transport	52%
Agriculture	44%
Industry	27% (Unconditional)
Waste Management	14%

Source: Prepared by the authors based on the Environmental Strategy 2024-2030 [5]

The ambitious targets presented in table 3, particularly in the energy and industry sectors, necessitate a sophisticated accounting infrastructure to track and verify progress. This highlights the critical role of implementing IFRS or aligning NAS with the requirements of Directive (EU) 2022/2464(CSRD)[4]: while National Accounting Standards (NAS) are insufficient for capturing the complex environmental liabilities and carbon-related risks associated with these targets, IFRS provides the 'fair value' and 'materiality' frameworks required for such high-level disclosures.

✓ **National GHG Monitoring and Reporting System:** By updating the mandate of the Environmental Agency, the Executive has aligned national emission inventories with the Paris Agreement and Energy Community obligations. This creates the technical infrastructure necessary for entities to access reliable secondary data for their own sustainability reports [6].

✓ **Sustainable Public Procurement (EU4Environment):** A strategic initiative aiming for at least 15% of public procurement to meet sustainability criteria by 2026. This exerts indirect pressure on the private sector to adopt ESG standards to remain eligible for state contracts [7].

✓ **Corporate Governance Reforms:** The legislative project voted in December 2024 aims to harmonize national corporate practices with EU standards, emphasizing transparency and board accountability. The **Model Code of Corporate Governance** (ratified by Government Decision No. 820/2023) establishes standardized practices for transparency, internal control, and shareholder rights for both state-owned and private enterprises, addressing the 'Governance' (G) pillar of ESG [8].

The primary barrier to effective ESG integration in Moldova is the existence of "institutional voids"—structural inefficiencies, limited institutional capacities, and regulatory ambiguity. Key organizations, such as the Environmental Agency and the Inspectorate for Environmental Protection, face constraints including insufficient personnel and overlapping mandates, which hinder the enforcement of environmental regulations and the conduct of thorough impact assessments[1,2,5]. Furthermore, as of late 2025, many administrative procedures remain paper-based, with only a small fraction of customs and environmental authorizations operational in electronic format. Bridging this digital gap is an essential prerequisite for the "data-driven institutionalization" of ESG required by the CSRD.

For SMEs in Moldova, which operate with limited resources and face weak regulatory pressure, the adoption of ESG is often driven by visionary leadership. These leaders reframe institutional gaps as strategic opportunities, using role-modeling and individualized support to embed sustainability into daily operations. By focusing on data visibility and accountability, these firms can evolve from minimal compliance to substantive governance, thereby reducing the risk of greenwashing and increasing their competitiveness in global supply chains.

Although the NAS are based on IFRS and oriented toward external stakeholders, they remain focused on financial performance. This creates a structural limitation when attempting to integrate ESG metrics, which require a broader non-financial reporting framework. In contrast, ESG reporting is value-driven, targeting a broad spectrum of stakeholders (investors, creditors, and civil society). The transition to ESG reporting is intrinsically linked to the accounting framework used by the entity. In the Republic of Moldova, IFRS serves as the 'gateway' to ESG disclosure; its principle-based nature and focus on fair value and transparency provide the necessary data architecture for sustainability reporting. Conversely, the National Accounting Standards (NAS) are not yet aligned with the non-financial disclosure mechanisms required by the CSRD, creating a significant 'reporting vacuum' for the majority of local entities.

While NAS is designed to capture quantitative, monetary-based transactions, ESG reporting requires the collection of granular, non-financial metrics (e.g., greenhouse gas emissions, social impact indicators, and board diversity). Most Moldovan enterprises lack the digital maturity and specialized software (such as integrated ERP systems) necessary to track these data points in real-time. This technological asymmetry increases the cost of compliance, particularly for Small and Medium Enterprises (SMEs) that form the backbone of the national economy.

The Moldovan accounting profession is predominantly trained in rule-based reporting (NAS), which offers limited room for professional judgment. However, international standards like IFRS S1 and S2 are principle-based and require a high degree of subjective assessment regarding materiality and climate-related risks. There is a significant shortage of locally certified ESG auditors and sustainability officers capable of translating environmental risks into financial language, creating a human capital bottleneck in the transition process.

A major limitation in the Moldovan landscape is the absence of independent assurance for sustainability disclosures. While systemic leaders (e.g., the banking sector) have begun voluntary reporting, these documents are rarely subjected to rigorous external audits. Without a national framework for ESG assurance, local reports face the risk of being perceived as "greenwashing", which undermines their utility for international green funds and institutional investors.

Moldova's banking sector, exemplified by institutions like MAIB S.A., has taken significant steps toward ESG integration. Influenced by the increasing demand for ESG-oriented assets in Europe, these institutions are beginning to monitor debt sustainability and increase the transparency of their balance sheets. This shift is not only a response to international investment pressure but a strategic move to lower equity capital costs and enhance reputation in a volatile regional market [9].

Moldcell S.A. represents the "Social" dimension of ESG leadership in Moldova. Through its commitment to digital inclusion and social impact, the company aligns its business model with the needs of the Moldovan population while adhering to international corporate governance standards. This alignment fosters stakeholder trust and enhances the company's resilience during periods of economic disruption [10].

Purcari Wineries PLC serves as a benchmark for ESG compliance within the Moldovan manufacturing and agricultural sectors. As a company listed on the Bucharest Stock Exchange (BVB), Purcari is legally mandated to adhere to rigorous transparency requirements, including IFRS-compliant financial statements and comprehensive non-financial disclosures. Their reporting framework goes beyond local requirements, integrating climate-related risks (TCFD) and water management metrics—critical factors for the viticulture industry [22]. This level of transparency is essential for maintaining investor confidence on an international regulated market and illustrates how cross-border listing acts as a catalyst for the rapid adoption of EU sustainability directives (CSRD) even for entities with core operations in Moldova.

The integration of ESG reporting within the Republic of Moldova is not merely a technical adjustment but a paradigm shift that faces significant institutional and structural barriers. The transition from the National Accounting Standards (NAS) — which are historically conservative and fiscal-oriented — to the investor-oriented IFRS/ESG framework reveals four critical gaps: regulatory, institutional, digital and market.

To bridge these gaps and ensure alignment with European sustainability trends, the transition should be structured across the following four strategic pillars:

- *Phase 1: Institutional alignment and phased mandate (ESRS based).* The Government, through the Ministry of Finance, should establish a clear timeline for mandatory ESG disclosure., aligned with the ESRS framework developed by EFRAG.

Priority: Start with Public Interest Entities (PIEs) that already report under IFRS (banks, insurance entities, and listed entities). For these entities, the implementation should follow the full ESRS or the Simplified ESRS for listed entities (LSME), as provided by EFRAG, to ensure international comparability [24].

Action: Transpose the EU's CSRD into national legislation, utilizing the EFRAG templates as the technical basis for reporting. This approach should allow a 2-3 year grace period for large non-listed companies currently using NAS, facilitating a gradual transition from financial-only reporting to integrated sustainability disclosures.

- *Phase 2: Development of "ESG-Lite" for SMEs.* Given that SMEs represent over 90% of the Moldovan economy, the complexity of full ESRS remains a prohibitive barrier.

Action: Moldova should adopt the VSME (Voluntary SME) framework, as developed by EFRAG[14], to serve as a simplified reporting template for non-listed entities. This "ESG-

Lite" approach focuses on essential metrics—such as energy efficiency, labor safety, and basic governance—allowing Moldovan SMEs to maintain their position within European supply chains.

As previously analyzed in the context of institutional transformations, this model allows smaller businesses to enhance transparency without facing excessive administrative burdens[25].

- *Phase 3: Capacity Building and Academic Integration.* To address the professional expertise gap, a systemic educational effort is required.

Action: Academic institutions, such as the Academy of Economic Studies of Moldova (ASEM), should integrate specialized ESG modules into accounting and management curricula, following the strategic framework for modernizing higher accounting education [23,p.7-11]. Furthermore, professional bodies (ACAP, etc.) should launch certification programs for "Sustainability Officers" to build a local pool of experts.

- *Phase 4: Digitalization and Centralized Data Governance.* To reduce information asymmetry and attract green funds, Moldova needs a transparent data infrastructure.

Action: Create a National ESG Digital Portal, managed by the National Bureau of Statistics or a dedicated agency. This platform would allow companies to upload standardized ESG data (using XBRL format), providing international investors with a "single source of truth" regarding Moldova's sustainability performance.

To overcome these barriers, the Republic of Moldova must implement an "adaptive ESG reporting model" that reduces the compliance burden for small players while providing the financial incentives, advisory services, and education needed for successful integration.

For Moldovan entities, particularly SMEs, the transition to ESG reporting involves significant compliance costs and barriers that differ from those faced by developed-market firms.

6. Conclusion

In conclusion, bridging the identified structural and institutional gaps requires a stratified approach that prioritizes the adoption of EFRAG standards (LSME and VSME) as the technical foundation for alignment with European directives. By leveraging the reporting expertise of IFRS-adopting entities and integrating sustainability into both academic curricula and digital infrastructure, Moldova can transform its current 'reporting vacuum' into a transparent ecosystem capable of attracting green capital and ensuring long-term economic resilience.

While the Moldovan ESG landscape is currently in its nascent stage, the rapid alignment with the *acquis communautaire* and the proactive stance of systemic leaders — such as MAIB, Purcari Wineries and Moldcell — provide a credible foundation for institutional change. However, the transition remains fragile, caught between the rigid legacies of fiscal-oriented accounting (NAS) and the transparent, forward-looking demands of international markets (IFRS/ESG). The proposed Roadmap offers a pragmatic path to bridge this 'implementation gap' by prioritizing institutional alignment and digital integration.

Ultimately, the success of this paradigm shift will depend on the government's ability to transform ESG from a 'check-the-box' compliance exercise into a core driver of national economic resilience and global competitiveness.

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Stochastic Modeling of Cyber Resilience in Smart Power Grids Using Continuous-Time Markov Chains

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Abstract. This article introduces a stochastic model for evaluating the resilience of smart power grids against cyberattacks aimed at distorting data flows. The model is grounded in continuous-time Markov chains (CTMC) and captures the probabilistic transitions of the system from normal operation to states of local degradation, large-scale compromise, and ultimately functional failure. The analysis provides a comprehensive treatment of attack propagation mechanisms, including the compromise of meters and concentrators, telemetry substitution, and the exploitation of asynchronous notifications, thereby enabling the representation of both direct and cascading effects. The proposed framework delivers a quantitative assessment of incident likelihood, recovery time, and expected impact, with explicit consideration of metrics such as Data Integrity Loss (DIL) and analogues of well-established energy reliability indices, including Expected Unserved Energy (EUE) and Loss of Load Probability (LOLP). Particular emphasis is placed on the economic dimension: the modeling results demonstrate the existence of a critical investment range in cybersecurity, within which the return on investment is maximized while costs remain minimal. The practical significance of this work lies in its potential application to the development of corporate information security policies, the adaptation of national regulatory standards, and the design of decision support systems for the energy sector.

Keywords. Cyber resilience, smart grids, continuous-time Markov chains, risk assessment, information security.

1. Introduction

The development of smart power grids (Smart Grids) represents a key direction in the digital transformation of the energy sector. These systems integrate distributed generation sources, including renewables, and enable bidirectional interaction with consumers. Unlike traditional power systems, the Smart Grid functions as a cyber-physical system in which energy transmission processes are closely coupled with information flows. This integration provides opportunities for improving energy efficiency and infrastructure reliability, while at the same time increasing vulnerability to cyber threats.

Ensuring the information security of smart power grids has become a strategic priority, as disruptions in the operation of their digital components can trigger large-scale supply failures and cause substantial socio-economic damage. In the context of the growing number of cyberattacks targeting critical infrastructure, the development of methods to enhance the cyber resilience of the Smart Grid is acquiring particular urgency.

The objective of this study is to develop a stochastic modeling framework for assessing the cyber resilience of smart power grids, providing a foundation for both risk evaluation and the formulation of protective strategies.

To achieve this objective, the following tasks are to be addressed:

- Conduct an analysis of threats and vulnerabilities of cyber-physical components in the Smart Grid.
- Examine existing international standards and best practices for the protection of critical infrastructure.
- Develop a methodology for assessing the cyber resilience of the power grid.
- Perform validation of the proposed approach using model scenarios or an experimental testbed.

The scientific contribution of this research lies in the development of an integrated probabilistic framework for ensuring the cyber resilience of smart power grids, which combines probabilistic mathematical modeling, risk-oriented analysis, and alignment with established information security standards. In contrast to the majority of existing studies, the proposed approach goes beyond mere threat identification based on a continuous-time Markov chain (CTMC) model that explicitly captures the interdependence between energy and information subsystems and links attack dynamics to operational reliability metrics (DIL, MTTD, MTTR, EUE-analogue).

The relevance of the study is shaped by the convergence of two pressing factors: the urgent need to digitalize the energy sector to enhance efficiency and sustainability, and the escalating risks of cyberattacks capable of undermining the very advantages of Smart Grid deployment. To bridge this gap, the present research contributes an interdisciplinary methodology that unites energy engineering with information technology, offering both theoretical advancement and practical value for critical infrastructure protection.

2. Analysis of Critical Data Flows and System Architecture

The conducted analysis of data flows and system architecture has revealed several critical points in the “meter–concentrator–data center” chain that require increased attention from the perspective of both information and technical security.

The most vulnerable components are the communication channels that employ power line communication (PLC) and wireless technologies with insufficient protection. Interception or substitution of data transmitted through these channels can result in widespread falsification of measurements, disruption of load-balancing processes, and even local power supply interruptions.

At the communication layer, which is responsible for aggregating and balancing distributed generation, security breaches may prevent real-time data on electricity production and consumption from reaching the control center. Such disruptions can lead to mismatches between generation and demand, an increased number of emergency situations, and reduced stability of the entire power system.

Asynchronous notification mechanisms are designed to transmit critical events to the data center, such as alerts on equipment failures or signs of tampering. However, once compromised, these channels may be exploited by adversaries to inject false signals. Consequently, disinformation attacks can be launched, provoking incorrect responses from operators or automated control systems [6]-[10].

3. Resilience Model of the Power Grid under Cyberattacks

The proposed model describes the probabilistic dynamics of a power grid under cyberattacks targeting its information flows. Particular attention is given to the system’s transition from normal operation to states of degradation and, ultimately, to functional failure (“data-driven blackout”) caused by the loss of data integrity.

The model takes into account the following factors:

- the frequency of attacks on communication channels and data aggregation nodes;
- the probability of successful compromise of meters, concentrators, or the control center;
- the propagation of attacks within the network, including false event injection and cascading errors;
- processes of detection, response, and recovery (such as patching, switching to backup channels, and equipment replacement).

For formalization, the model employs a continuous-time Markov chain (CTMC) [1]-[5] with aggregated states. When necessary, the framework can be extended to semi-Markov or phase-type models in order to capture non-exponential detection, response, and recovery times associated with cyberattacks.

4. Model States

Within the framework of the proposed model, four states are distinguished:

S_0 – Normal Operation. All data remain reliable, and control processes are performed correctly.

S_1 – Local Compromise. A subset of devices is compromised; data are partially distorted, and restrictive measures are applied.

S_2 – Large-Scale Compromise. Telemetry substitution and false notifications become systemic, creating risks of incorrect control commands and mismatches between generation and load.

S_3 – Functional Failure. Control becomes impossible due to the loss of data integrity; the consequences are comparable to a blackout.

State Transitions

The transitions of the system from one state to another are described by transition rates (measured in units of 1/hour), which reflect the probability that a change of state will occur within a short time interval. These transition rates enable the formalization of the process using continuous-time Markov chains and provide a means to link the system's technical parameters with the probabilities of incidents.

Compromise Transitions

$S_0 \rightarrow S_1$:

$a_{01} = \lambda p_c a$, where λ is the attack frequency and p_c is the probability of a successful attack. This rate represents the likelihood that, given a certain attack frequency (λ) and probability of success (p_c), the system transitions from normal operation to local degradation. In essence, the more frequent the attacks and the higher the success rate, the faster individual devices (meters or concentrators) are compromised.

$S_1 \rightarrow S_2$:

$a_{12} = \lambda p_c k_{12}$, where k_{12} reflects the complexity of attack propagation. At this stage, the attack escalates from a local issue to a systemic compromise. The coefficient k_{12} reduces the transition rate, reflecting the additional effort required for an adversary to propagate the attack (e.g., spreading from one concentrator to adjacent nodes).

$S_2 \rightarrow S_3$:

$a_{23} = \lambda p_c k_{23}$. This stage corresponds to a complete informational collapse: control loses reliability, and the risk of a “functional blackout” emerges. The coefficient k_{23} is typically smaller than k_{12} , since achieving a full-scale system failure is more difficult than compromising a portion of the infrastructure.

Internal Propagation (Cascade Effects)

$$S_1 \rightarrow S_2: \gamma_1$$

Even if the attack does not escalate directly through new compromise attempts, the system may deteriorate due to internal cascading effects. For example:

- an adversary substitutes several meter messages,
- the concentrator interprets them as legitimate problems,
- the control center reacts incorrectly, thereby amplifying the degradation.

The parameter γ_1 reflects precisely such “self-developing” errors. It represents the likelihood that a local disruption evolves into a systemic compromise due to the internal dynamics of the network.

$$S_2 \rightarrow S_3: \gamma_2.$$

At this stage the situation becomes even more severe: an existing large-scale compromise may, by itself, lead to a complete loss of controllability. For instance:

- false alarm events overload operators,
- automatic control systems receive contradictory data and execute erroneous switching actions,
- as a result, the system experiences an abrupt transition to a “functional blackout.”

Thus, the parameter γ_2 represents the risk that, even in the absence of new external attacks, cascading internal failures can drive the network into total collapse.

Detection and Recovery

$$S_1 \rightarrow S_0: \mu_1.$$

This parameter corresponds to rapid recovery measures, where local compromise (e.g., an infected meter or concentrator) is promptly detected and isolated. In such cases, administrators can disconnect the compromised device, clean it, or roll back its configuration. The parameter μ_1 represents the recovery rate, i.e. the intensity of returning from S_1 to S_0 . A higher value of μ_1 corresponds to a shorter mean recovery time, thereby reducing the likelihood that a local attack will escalate into a systemic compromise.

$$S_2 \rightarrow S_1: \mu_2.$$

This case involves more complex incidents in which the compromise has already spread further. Recovery requires substantial measures such as reissuing access keys, replacing firmware or hardware, or re-establishing trusted communication channels. The recovery rate μ_2 is typically lower than μ_1 , reflecting longer mean recovery times. It formally quantifies the organization’s ability to cope with severe cyberattacks.

$$S_3 \rightarrow S_1: \rho_1.$$

Recovery from the functional failure state S_3 may proceed through direct transitions to S_0 or S_1 ; however, staged recovery via S_2 is explicitly relevant and can be integrated into the model to better reflect real-world processes.

Parameter Semantics (CTMC Rates)

In a continuous-time Markov chain, each off-diagonal element q_{ij} is a transition rate (hazard). For state S_i , the mean sojourn time equals $1/(-q_{ii})$. Accordingly, μ_1 , μ_2 , ρ_0 , and ρ_1 are rates of recovery transitions:

- μ_1 – rate from S_1 to S_0 (local recovery),
- μ_2 – rate from S_2 to S_1 (de-escalation),
- ρ_1 – rate from S_3 to S_1 (emergency partial restoration),
- ρ_0 – rate from S_3 to S_0 (full restoration).

Additionally, δ denotes the detection rate. It is explicitly included in the generator matrix Q and directly contributes to the recovery transitions ($S_1 \rightarrow S_0$ and $S_2 \rightarrow S_1$), thereby ensuring transparency and completeness of the model

If one wishes to discuss times rather than rates, the corresponding mean recovery times are $1/\mu_1$, $1/\mu_2$, $1/\rho_1$, and $1/\rho_0$.

The dynamics are governed by the CTMC generator Q where each diagonal element is defined as $q_{ii} = -\sum_{i \neq j} q_{ij}$, ensuring that the row sums equal zero. The explicit form of the generator is as follows (1):

$$Q = \begin{bmatrix} -a_{01} & a_{01} & 0 & 0 \\ \mu_1 - (\mu_1 + a_{12} + \gamma_1) & a_{12} + \gamma_1 & 0 & 0 \\ \mu_2 - (\mu_2 + a_{23} + \gamma_2) & a_{23} + \gamma_2 & \rho_0 & \rho_1 \\ 0 & 0 & -(\rho_0 + \rho_1) & 0 \end{bmatrix} \quad (1)$$

Here:

For state S_0 : $q_{00} = -a_{01}, q_{01} = a_{01}$.

For state S_1 : $q_{11} = -(\mu_1 + a_{12} + \gamma_1)$, $q_{10} = \mu_1$, $q_{12} = a_{12} + \gamma_1$.

For state S_2 : $q_{22} = -(\mu_2 + a_{23} + \gamma_2)$, $q_{21} = \mu_2$, $q_{23} = a_{23} + \gamma_2$.

For state S_3 : $q_{33} = -(\rho_0 + \rho_1)$, $q_{30} = \rho_0$, $q_{31} = \rho_1$.

This formulation ensures that each row of Q sums to zero, thereby satisfying the fundamental property of CTMC generators.

Initial distribution: $p(0) = [1, 0, 0, 0]$.

Time evolution: $p(t) = p(0)e^{Qt}$.

Stationary distribution: $\pi Q = 0, \sum \pi_i = 1$.

Based on the model, one can compute:

- the probability of functional failure by time t (2):

$$P_{BL}(t) = p_3(t) \text{ (the } S_3 \text{ component)}. \quad (2)$$

- the **Data Integrity Loss (DIL)** — the expected fraction of unreliable data;
- the mean time to detection (MTTD) and mean time to recovery (MTTR);
- the expected impact of distorted data on power supply (an analogue of **Expected Unserved Energy, EUE**).

Metrics and Evaluation Procedures (DIL, MTTD, MTTR, EUE-analogue)

The proposed CTMC-based model allows the derivation of quantitative resilience indicators that capture both reliability and security aspects of smart grid operation under cyberattacks.

This metric measures the expected share of corrupted or unreliable data. It is defined as the weighted probability of being in a compromised state (S_1 – S_3) (3):

$$DIL(t) = p(t) w^T, \quad (3)$$

where: $p(t) = [p_0(t), p_1(t), p_2(t), p_3(t)]$ is the probability distribution over states at time t , $w = [w_0, w_1, w_2, w_3]$ is the weighting vector that specifies the relative share of unreliable data in each state. By convention, $w_0 = 0$ (no data corruption in the normal state), while $w_3 = 1$ corresponds to complete data loss in state S_3 .

Typical assumptions: $w_1 \ll w_2 < 1$, reflecting that local compromise leads to minor distortion, large-scale compromise entails significant corruption, and functional failure implies total loss of data integrity.

MTTR (Mean Time to Recovery) denotes the expected time required to restore the system to a stable operational state following a compromise. In addition, for specific scenarios, a partial recovery time (pMTTR) can be defined for the subset of states $\{S_1, S_2\}$. This avoids confusion between full and partial recovery times (4):

$$T = -Q_{TT}^{-1} \mathbf{1} \quad (4)$$

If a scalar MTTR is required for a given initial distribution α over the transient states, it is computed as $MTTR = \alpha T$.

Analogous to the reliability index Expected Unserved Energy (EUE), this metric reflects the expected impact of compromised data on power supply. Each state S_i is assigned an energy loss factor c_i , corresponding to the proportion of demand potentially mismanaged. The expected unserved energy is then (5):

$$EUE(t) = p(t)c^T, \quad (5)$$

where $c = [0, c_1, c_2, c_3]$. Here

c_1 reflects minor inaccuracies in load balancing,

c_2 accounts for systemic miscoordination,

$c_3 \approx 1$ corresponds to blackout-level disruption.

Interpretation:

DIL quantifies the *data-level integrity degradation*.

MTTD and **MTTR** characterize *operational responsiveness*.

EUE-analogue links the cyber perspective with *energy supply consequences*.

Together, these indicators provide a comprehensive assessment of cyber resilience by connecting **attack dynamics** (λ, p_c, γ) with operational outcomes (availability, reliability, and socio-economic impact).

5. Practical Application of the Model Analysis of Cyberattack Scenarios

The developed model makes it possible to examine in detail various cyberattack scenarios targeting the power system and to forecast their consequences.

Frequent but low-impact attacks

Such attacks do not lead to severe consequences but impose a constant load on detection and response subsystems. The model shows that when the attack frequency (λ) is high but the success probability (p_c) is low, the likelihood of the system reaching critical states (S_2 – S_3) remains minimal. At the same time, the risk of overloading monitoring subsystems and generating false alarms increases.

Rare but targeted campaigns

When attacks occur infrequently but with high efficiency (high p_c), the probability of rapid escalation to large-scale compromise and functional failure rises significantly. Under such conditions, the key resilience factors are detection speed (δ) and recovery rates (μ_2, ρ).

Combined attacks (technical + social engineering).

This scenario is characterized by an increase not only in the probability of success (p_c) but also in the cascading coefficients (γ_1, γ_2). Social engineering may grant attackers access to internal systems, substantially raising the risk of escalation. The model confirms that such hybrid attacks pose the most severe threat to power grids.

Exploitation of asynchronous notifications

In this case, the parameter γ_1 rises sharply. The system may treat false events as genuine incidents, leading to cascading disruptions. Simulation results indicate that under high values of γ_1 , even local compromises can evolve into systemic crises.

Conclusion: The key resilience factors across most scenarios are the speed of detection and recovery, as well as the reduction of compromise probability through regular patching and communication channel segmentation [6], [9].

6. Economic Efficiency of Investments

The model enables not only the forecasting of attack consequences but also the evaluation of the economic efficiency of various cybersecurity measures.

The analysis results revealed the existence of a critical investment range. Simulation results under assumed parameter values indicate that simulation experiments under assumed parameter values suggest the existence of a critical investment range. Illustrative simulations suggest the existence of a potential investment threshold, where increasing cybersecurity expenditures significantly reduces expected damage, while further increases show diminishing returns. The specific figures (e.g., 20% of the IT budget) are scenario-dependent and require validation with empirical data. These values are illustrative and depend strongly on the assumptions regarding attack frequency, success probability, and recovery rates.

This outcome has important practical implications:

- it supports the development of an optimal strategy for resource allocation;
- it confirms the necessity of applying methods of economic and mathematical analysis to identify priority protection areas;
- it helps to avoid both underinvestment (insufficient protection) and overspending with low marginal effectiveness.

7. Practical Significance

The proposed models can be applied in the following contexts:

- in the formation of corporate cybersecurity policies for energy companies;
- in the adaptation of national and sectoral information security standards to the conditions of energy digitalization;
- as a foundation for the development of decision support systems focused on risk management and cost optimization.

Thus, the proposed methodology combines technical and economic modeling, thereby providing a comprehensive approach to the problem of cyber resilience in energy infrastructure.

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Investments in Moldova's Energy Infrastructure: Priorities and Modernization Prospects

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Abstract. The article examines investments in Moldova's energy infrastructure as a key factor for its modernization and sustainable development. The current state of the infrastructure, main directions, and investment priorities are analyzed, including the development of power grids, renewable energy sources, storage systems, and digitalization. Special attention is given to financing sources and the role of international organizations in supporting the modernization of the sector. The prospects for the development of Moldova's energy system are outlined in the context of integration into the European energy market and the transition to a low-carbon economy.

Keywords. Energy infrastructure; Energy investments; Renewable energy sources; Power grids; Energy storage systems.

1. Introduction

The modernization of energy infrastructure is a crucial factor in ensuring sustainable economic growth and energy security. For the Republic of Moldova, this issue is particularly relevant due to its high dependence on energy imports, outdated infrastructure, and the strategic objective of integration into the European energy market. More than two-thirds of Moldova's electricity demand is covered by external sources, while domestic generation capacities remain limited and are largely based on fossil fuels or facilities inherited from the Soviet period. In this context, investments in modern energy infrastructure represent both an economic necessity and an opportunity to align with the objectives of the European Union's Green Deal.

The purpose of this article is to analyze the current state of Moldova's energy infrastructure, identify investment priorities, and assess modernization prospects in accordance with advanced international experience.

Current State of Moldova's Energy Infrastructure

Moldova's electricity sector is characterized by a high dependence on imports and the absence of diversified domestic generation. A significant share of electricity supply was provided by the Moldavian GRES power plant until 2025, located in the Transnistrian region, which created both economic and political vulnerabilities. Since 2025, a larger share of electricity has been supplied from Romania. Renewable energy sources (RES), mainly solar energy and biomass, account for a small but steadily growing share of the energy mix.

Transmission and distribution networks face serious challenges. According to national statistics, electricity losses in transmission and distribution are among the highest in the region, reaching 11–12%. Many power lines, substations, and transformers were built more than 30 years ago and require urgent modernization. Limited grid capacity also constrains the integration of new renewable energy projects [13].

2. Research results

As we can see, 17% of the required electricity was purchased on the exchange. During the winter months, purchases on the exchange reached 25%.

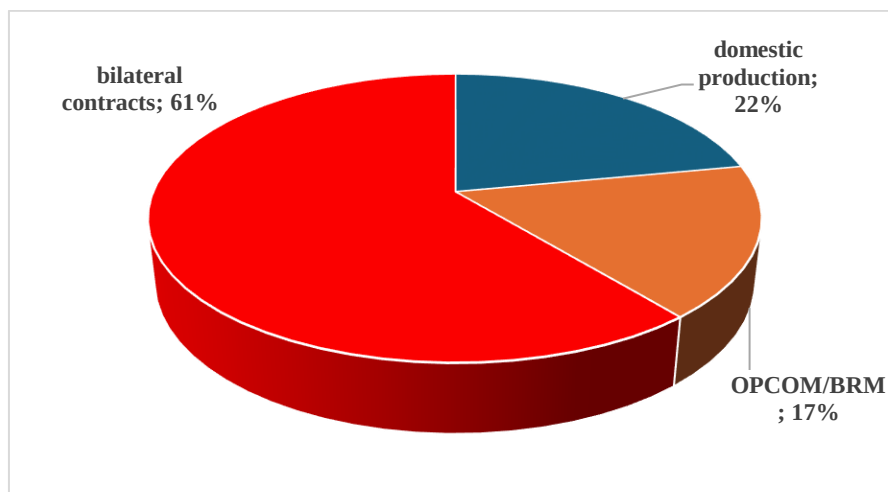


Figure 1. The current state of Moldova's energy infrastructure
Source: compiled by the author based on data from <https://energocom.md>

Table 1. Electricity consumption and generation from renewable energy sources in Moldova

Indicators	Unit	2020	2021	2022	2023	2024
Total amount of purchased electricity	million kWh	4 269,80	4 591,70	4 512,90	4 333,10	4 626,10
% change	%		8%	-2%	-4%	7%
Production	million kWh	851,4	984,7	851,1	1 010,80	1 340,80
% change	%		16%	-14%	19%	33%
Attitude to purchased energy	%	20%	21%	19%	23%	29%
of which from renewable energy source	million kWh	129,9	186,8	239,6	407,3	643,1
% change	%		44%	28%	70%	58%
Attitude to purchased energy	%	3%	4%	5%	9%	14%

Source: compiled by the author based on data from <https://anre.md>

Electricity consumption increased slightly, while production from renewable energy sources reached 14% in 2024. Moreover, 70% of energy is imported either from Ukraine and Romania or from state district power plants.

The amount of energy entering the grid has increased in recent years. Until 2025, the majority of this energy came from the Moldavian Regional Power Plant (MGRES). Since 2025, imports from Romania have increased, as have those from renewable energy sources. In the first half of 2025, the volumes have equaled those for the entire year of 2024. We have also observed an increase in process losses in recent years.

Table 2. The amount of electricity received by the transmission network of Moldova

Indicators	2019	2020	2021	2022	2023	2024	2 кв 2025
The amount of electrical energy supplied to the transmission grid, million kWh	4294,5	4254,4	4550,6	4427,97	4617,51	5014,2	2413,8
inclusive:							
MGRES, million kWh	2856,8	3251,3	3445,6	2708,34	3293,7	3093,6	0
Thermal power plant, million kWh	659,6	721,5	797,7	611,52	603,1	698	424,2
Renewable energy, million kWh	134,1	114,5	145,8	153,02	261,51	478,3	453,4
Import, million kWh	644	167,1	161,5	955,09	459,2	744,3	1536,2
Technological losses %	2,48%	2,43%	2,56%	3,66%	4,05%	14,82%	6,90%

Source: compiled by the author based on data from <https://www.moldelectrica.md/anre.md>

Table 3. Length of overhead electrical lines in Moldova

Length of overhead electrical lines	2019	2020	2021	2022	2023	2024	2 кв 2025
35 kV	807,59	807,59	807,59	807,59	807,59	668,3	668,3
110 kV	3337,04	3337,04	3337,04	3337,04	3337,04	2818,37	2818,37
330 kV	377,34	377,34	377,34	377,34	377,34	377,34	377,34
400 kV	203	203	203	203	203	203	203
Number of power transformers in operation	648	650	650	649	650	650	650
Total capacity of power transformers in operation	4750,2	4775,2	4775,2	4650,5	4641,5	4641,5	4656,5

Source: compiled by the author based on data from <https://www.moldelectrica.md>

As we can see, the length of overhead lines decreased in 2024, especially between 110 kV and 519 kV. The number of power transformers remained virtually unchanged, while their capacity decreased. Given the growth in energy consumption and the variety of supplies, the need for investment in new lines and transformers is only increasing (most networks and equipment are over 30 years old).

Table 4. Investments approved by ANRE and executed

Indicators	Operator	Unit	2019	2020	2021	2022	2023	2024
Transmission System Operator	Î.S. „Moldelectrica”	thousand lei	380 392	136 881	88 280	16 753	161 540	700 964
Distribution system operators	Î.C.S. „Premier Energy Distribution” S.	thousand lei	259 710	321 136	258 142	245 599	311 486	389 648
	S.A. „RED Nord”	thousand lei	255 217	236 834	270 456	198 379	219 347	236 474
Universal service providers and providers of last resort	Î.C.S. „Premier Energy” S.R.L.	thousand lei	454	3 455	772	965	1 505	729
	S.A. „Furnizarea Energiei Electrice Nord”	thousand lei	202	66	378		96	4 000
Total			895 975	698 372	618 028	461 696	693 974	1 331 815

Source: compiled by the author based on data from www.moldelectrica.md/anre.md

As we can see, investment in power grids declined during the pandemic and has increased significantly over the past two years, more than doubling. This is primarily due to Moldelectric.

Let's look at the structure of renewable energy capacities commissioned in Moldova at the end of July 2025

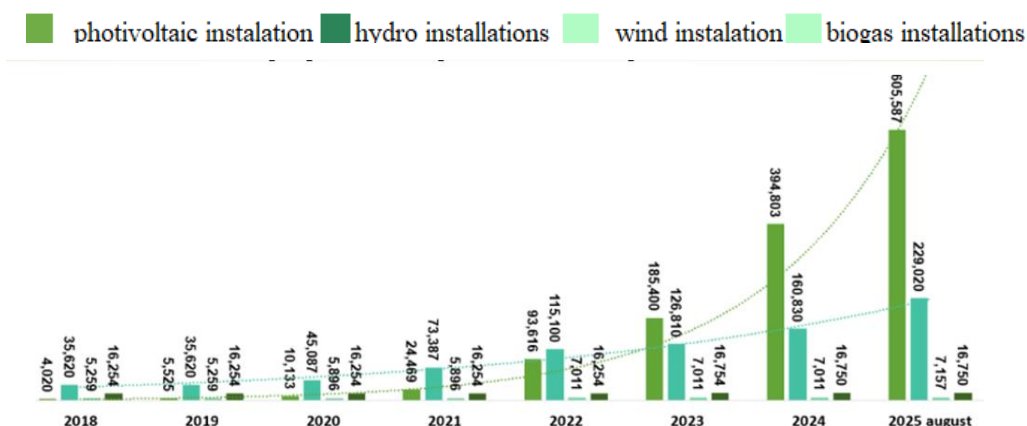


Figure 2. Investment priorities in the energy sector
Source: compiled by the author based on data from <https://cned.gov.md>

As we can see, the growth of commissioned capacities has increased, especially solar panels and slightly less wind power plants.

	Producer					TOTAL
	Law 160-XVI/2007	Law 10/2016/fixed tariff	Free market	Net Accounting	Net invoicing	
Solar panels	0,59	139,62	241,38	115,31	48,71	545,61
Wind power plants	27,23		187,35			214,58
Biogas	5,17	1,99				7,16
Hydropower	0,25		16,5			16,75
Total	33,24	184,11	439,94	115,31	58,43	784,09

Figure 3. Capacity of renewable energy power plants commissioned at the end of July 2025
Source: compiled by the author based on data from <https://cned.gov.md>

Compared to 2024, capacity has increased by 46%. This is primarily due to the expansion of solar panels and, to a lesser extent, wind power plants.

With the increasing deployment of new renewable energy capacity, particularly solar power plants and wind power plants, the imbalance between electricity production and consumption is widening. Solar power plants produce variable amounts of electricity depending on the season and time of day, as well as the current weather conditions.

Therefore, there is a need to improve energy transmission and storage infrastructure.

Smart grid is a digital power grid management system that enables real-time balancing of supply and demand, integration of renewable energy sources (RES), and increased energy efficiency. It utilizes sensors and smart meters. For Moldova, this means increasing grid flexibility and readiness for the growing share of RES.

Cross-border connections: lines with Romania (Vulcanesti-Isaccea, Strasen-Vulcelele). To eliminate supply risks through the Transnistrian region and reduce losses, the Vulcanesti-Chisinau line is being built. Construction of the 400 kV Vulcanesti-Chisinau

overhead power line is ongoing. Eighty percent of the supports have been installed, and over 79 km of wires have been laid, representing 51% of the line's total length (157 km).[6]

The Strasen-Gutinas power transmission line, which will connect Moldova and Romania, will require \$130 million in investment.[8]

Next, another high-voltage line will be built between Balti and Suceava.

Battery parks and a study of pumped-storage hydroelectricity potential are also needed to improve infrastructure.

The installed renewable energy capacity of 720 MW at the end of July will allow for a 30% increase in consumption within 12 months, and during the summer months and with favorable weather, generation may exceed consumption.

We see increasing risks of an imbalance between production and consumption. This requires a well-developed grid interconnected with neighboring countries to transfer surplus energy and generate it when needed, or to develop energy storage systems.

Many European countries have faced such problems, forcing them to sell electricity at negative prices, limit production, or implement energy storage systems. Some European countries have been forced to limit renewable energy production.

In Europe, restrictions have increased in some places and are expected to increase further—research and analysis show that batteries can significantly reduce economic restrictions. Approximately, restrictions range from 3.5% to 10% depending on the region or country. European countries are attempting to reduce production restrictions through the introduction of energy storage systems or pumped hydroelectric power plants.

The impact of energy storage deployment varies across countries.

Spain: Modeling shows that 200 Wh batteries per 1 kW PV significantly reduce constraints; in some areas, this can be reduced by up to 80% (research estimate). According to another estimate, after the deployment of energy storage batteries, production constraints will be 0.5–1% (with a battery of ~200 Wh/kW PV).[14]

For Germany, estimates and analyst commentary have been published: batteries reduce negative price hours and contribute to grid flexibility; however, the scale of ESS is not yet sufficient to completely eliminate constraints—major capacity increases will be required. A reduction in negative hours and production constraints will occur with 2–5 GW of batteries (model estimate).[15] In Ireland, after the introduction of energy storage batteries, renewable energy generation constraints will decrease to 1–3% (depending on the battery)—empirical data.[16]

3. Prospects for modernization

Financing options:

International financial institutions (EBRD, EIB, World Bank, USAID, EU grants);

Attracting private capital through guarantees and tariff policy.

Country experiences:

Romania – rapid growth of RES with the support of green certificates;

North Macedonia – successful attraction of FDI to solar parks;

Bulgaria – problems with tariff policy as a lesson for Moldova.

4. Barriers and challenges

Financial: limited internal capital, high borrowing costs.

Regulatory: inconsistent tariff policy, unstable laws.

Technical: worn-out networks, lack of storage facilities.

Social: low consumer solvency, resistance to tariff increases.

5. Conclusion

Investments in energy infrastructure are key to sustainable economic growth.

Priority areas include energy storage, grid modernization, energy storage systems, and interconnectors.

Recommended actions:

Create a stable and transparent investment environment;

Strengthen partnerships with international organizations;

Implement European tariff incentive practices;

Develop public-private partnership mechanisms.

This will also lead to:

Increased GDP due to increased investment.

Job creation in the energy and construction sectors.

Reduced dependence on energy imports and increased energy security.

Increased competitiveness of enterprises due to reduced energy costs.

Improved environmental conditions (reduced carbon dioxide emissions).

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Mind Games and Machines: Social Engineering in the Cybersecurity Era

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Abstract. Social engineering, the deliberate manipulation of human psychology to obtain information, access, or actions that would otherwise be withheld, now underpins an estimated 98% of all cyberattacks (Sonowal, 2023). FBI IC3 data show cybercrime losses exceeding \$10.3 billion in 2022, with Business Email Compromise as the single largest category; IBM research places the average cost of a social-engineering-initiated breach above \$4 million (FBI IC3, 2023; Gururaj et al., 2024). Existing reviews predate the operational deployment of generative AI and deepfake synthesis as attack tools, and no integrated framework currently bridges psychological theory, an updated attack taxonomy, and AI-specific defense design. Drawing on Hadnagy (2011), Gray (2021), Sonowal (2023), and Gururaj et al. (2024), this paper traces social engineering from its historical origins through its AI-augmented present, maps the current attack taxonomy, examines the psychological mechanisms that make these attacks effective, and proposes a defense-in-depth framework that treats human behavior and technical controls as co-equal requirements. The paper's primary contribution is a synthesis connecting behavioral science, organizational design, and emerging AI threats in a single analytical frame applicable to practitioners and policymakers.

Keywords. Social engineering, phishing, deepfake, AI-augmented attacks, defense-in-depth.

1. Introduction

Ask a security engineer where breaches come from, and the answer will usually involve unpatched systems, misconfigured firewalls, or compromised credentials. Ask the attackers, and the answer is simpler: people. Social engineering, the art of manipulating individuals into surrendering access, information, or authorization they would otherwise protect, has been the dominant breach vector for over a decade, and its share of the attack surface is growing rather than shrinking. As technical defenses have matured, the return on investment from psychological manipulation has outpaced the return from technical exploitation. Hadnagy (2011, p. 8) states the logic plainly: no attacker is going to spend a hundred hours on a technical route when a well-crafted phone call achieves the same result in under an hour.

The FBI's IC3 reported losses exceeding \$10.3 billion from cybercrime in 2022, with Business Email Compromise accounting for the single largest category of financial harm (FBI IC3, 2023). An estimated 98% of cyberattacks rely on social engineering at some point in the kill chain (Sonowal, 2023, p. 2). IBM's 2022 breach cost data found that social engineering as an initial attack vector produced average incident costs above \$4 million, exceeding the mean for purely technical exploits (Gururaj et al., 2024). What transforms these figures from alarming to urgent is the trajectory: the convergence of social engineering with generative AI, voice and video synthesis, and automated open-source intelligence collection is producing a

threat landscape that the defense frameworks built over the past twenty years were not designed to handle.

No existing single-paper synthesis bridges psychological theory, a taxonomy updated to include AI-augmented vectors, and a defense framework designed for the current threat environment. This paper addresses that gap. The analysis draws on Hadnagy (2011), Gray (2021), Sonowal (2023), and Gururaj et al. (2024) as its primary sources, supplemented by FBI IC3 data, IBM breach cost research, and documented incident records.

2. Methodology

This paper employs a systematic narrative review methodology. Source selection followed three criteria: theoretical centrality, empirical grounding, and recency, with preference given to sources published after 2020 for empirical claims about attack prevalence and cost. Four primary texts form the theoretical core: Hadnagy (2011), which provides the foundational taxonomy and psychological framework; Gray (2021), which addresses practitioner methodology and OSINT-based attack construction; Sonowal (2023), which synthesizes the historical and definitional landscape alongside contemporary threat data; and Gururaj et al. (2024), which integrates AI-augmented attack analysis with organizational defense recommendations.

Empirical data on incident frequency, financial losses, and breach costs are drawn from the FBI IC3's annual Internet Crime Reports, IBM Security's Cost of a Data Breach series, and the CSIS Significant Cyber Incidents database. Three case studies were selected to maximize attack vector diversity: the 2011 RSA SecurID breach, the 2020 Twitter Bitcoin scam, and the 2024 Hong Kong deepfake fraud. This paper does not present primary empirical data; it is a synthesis and framework paper.

3. Historical and Conceptual Background

The history of social engineering is considerably older than the internet. The psychological mechanisms attackers exploit today are stable features of human cognition that have been exploited across every era of recorded history; they cannot be patched or engineered away. The Trojan Horse is the oldest documented case study: the Greeks did not breach Troy's walls, they persuaded the Trojans to breach them on the Greeks' behalf (Sonowal, 2023, p. 3). The term itself entered the English lexicon from Dutch industrialist J.C. Van Marken, who used *sociale ingenieurs* in 1894 to describe specialists who applied systematic discipline to the human dimensions of organizations (Sonowal, 2023, p. 3).

The twentieth century produced practitioners who advanced the discipline substantially. Victor Lustig's 1925 Eiffel Tower scheme combined forged documentation, a choreographed credibility-building process, and manufactured urgency in a sequence that modern BEC operators replicate almost exactly (Sonowal, 2023). Kevin Mitnick's penetrations of Nokia, Motorola, and U.S. Defense Department networks established that psychological acuity combined with technical knowledge produced an attack surface no firewall could address. As Hadnagy (2011, p. 8) observes, the economics have only become more favorable to attackers as technical defenses have hardened.

This paper uses Hadnagy's (2011) definition of social engineering: any act that influences a person to take an action that may or may not be in their best interest. Sonowal (2023) draws the important distinctions: social engineering differs from pure technical hacking in that it targets people rather than systems; from simple deception in that it involves a structured, multi-phase operational sequence. The distinction between social engineering and

phishing deserves particular emphasis, because treating them as synonymous produces defenses that address only a fraction of the actual attack surface.

4. The Psychological Architecture of Manipulation

Social engineering works reliably not because attackers are especially skilled manipulators but because they have learned to activate cognitive mechanisms that human beings share universally. Understanding the psychological architecture underlying social engineering is the prerequisite for designing defenses that actually interrupt attacks rather than simply making them marginally harder.

4.1 Cialdini's Principles of Influence

Robert Cialdini's (2006) six principles of influence remain the most cited and most operationally relevant framework in the social engineering literature. Gray (2021), Hadnagy (2011), and Sonowal (2023) all draw on them as primary analytical tools. Reciprocity creates a felt obligation to return favors; attackers activate it by providing something of apparent value before making a request. Authority triggers compliance with perceived power figures.

Social proof leads people to take behavioral cues from what they believe others are doing. Scarcity and urgency engage loss aversion directly. Liking raises compliance with people perceived as similar or warm. Commitment and consistency mean that a small initial agreement makes subsequent, larger compliance significantly more likely (Cialdini, 2006; Hadnagy, 2011).

4.2 Cognitive Biases

Alongside Cialdini's principles, attackers exploit a specific cluster of cognitive biases. The optimism bias leads individuals to underestimate their own probability of being targeted. The automation bias produces over-reliance on technical filters. The familiarity heuristic means that a sender name or visual identity that approximates a trusted source triggers approval before deeper scrutiny engages (Gururaj et al., 2024). Most consequentially, Hadnagy (2011) documents the deception detection deficit: human beings perform at approximately chance level — around 54% accuracy — when asked to identify deceptive communications. Any defense strategy that relies on trained employees detecting malicious intent from communication content alone is built on a foundation the research does not support.

4.3 Elicitation

Elicitation is the subtle extraction of information during an apparently normal and innocent conversation (Hadnagy, 2011, p. 98). Where phishing requires the target to perform a conscious action, elicitation produces voluntary disclosure: the target provides sensitive information without recognizing they are doing so. Hadnagy (2011, p. 99) documents a field example in which a complete operational picture of a target organization — including staffing structure, system names, and security practices — was assembled at a professional networking event through what the target believed was routine conversation.

5. A Comprehensive Attack Taxonomy

Social engineering is not a single technique but a structured family of tactics sharing psychological foundations while varying substantially in medium, technical requirements, and scale. The taxonomy below synthesizes classifications from Sonowal (2023), Gray (2021), Gururaj et al. (2024), and Hadnagy (2011), updated to reflect vectors that have reached operational maturity since those texts were written.

5.1 The Attack Lifecycle

Sonowal (2023) describes a six-phase operational lifecycle: (1) target selection based on role and access level; (2) OSINT-based information gathering using social media analysis, public records, Google dorking, and EXIF metadata extraction; (3) preparation of the pretext and delivery infrastructure; (4) trust development, which can require considerable patience (Gururaj et al., 2024, p. 33); (5) exploitation; and (6) exit and cover. By the time an attack reaches the exploitation phase, the psychological preparation is already complete. Effective defense must reach back into the reconnaissance and trust-development phases, not merely the moment of the lure.

5.2 Digital Attack Vectors

Phishing remains the highest-volume social engineering vector. Mass phishing distributes deceptive emails at scale; spear phishing trades volume for precision by incorporating OSINT-derived specifics. Gray (2021) describes constructing pretexts around live events in the target's environment. Whaling applies spear phishing precision to C-suite executives. Vishing adds a real-time interactive dimension that Hadnagy (2011) argues makes it more effective against security-trained recipients. Smishing exploits higher SMS open rates. Business Email Compromise impersonates internal executives to authorize wire transfers; the FBI IC3 reported \$2.7 billion in adjusted BEC losses in 2022 alone (FBI IC3, 2023).

Pretexting is foundational to virtually all social engineering. Hadnagy (2011) makes the case that every attack involves a fabricated scenario providing the attacker's request with plausible operational context. Physical social engineering- tailgating, dumpster diving, baiting with infected USB drives- is consistently underweighted in digital-first security frameworks, despite consistently succeeding in authorized penetration tests (Gray, 2021; Gururaj et al., 2024).

5.3 Target Demographics

Social engineering attacks are not randomly distributed. Sonowal (2023) shows that systematic profiling by role, access level, and information value is standard practice. Entry-level employees are targeted for their lack of institutional skepticism; senior executives for their authorization authority over wire transfers and policy overrides; help desk and IT staff specifically because their function involves granting access and resetting credentials.

6. The AI-Augmented Threat Landscape

Artificial intelligence has not altered the psychological principles that social engineering exploits. What it has changed is the cost, speed, and scale at which sophisticated attacks can be executed. Gururaj et al. (2024) characterize this as a qualitative shift rather than a quantitative increment.

6.1 AI-Generated Phishing

Large language models have effectively eliminated the surface-level anomalies that security awareness training has relied on for detection: grammatical errors, awkward phrasing, implausible sender identities. A model prompted with a target's LinkedIn profile and publicly available corporate communications can produce a spear-phishing message referencing authentic organizational events, real colleague names, and genuine internal systems. Gururaj et al. (2024) describe the consequence: the gap between mass phishing and spear

phishing is collapsing. AI now makes it operationally viable to run campaigns that have both volume and precision.

6.2 Deepfake Audio and Video

In 2019, a UK energy company transferred approximately £200,000 after the CEO received a call from a synthesized voice replicating his parent company's Managing Director. In February 2024, a Hong Kong-based multinational lost approximately HK\$200 million (USD \$25.6 million) when a finance employee authorized transfers following a video conference in which every other participant was an AI-generated deepfake constructed from publicly available footage of real executives. Hong Kong police confirmed this as the first publicly documented case of multi-participant deepfake personas used simultaneously in a real-time interactive fraud (Gururaj et al., 2024).

6.3 Automated OSINT

AI has compressed OSINT reconnaissance from hours to seconds. Automated tools now cross-reference social media profiles, corporate directories, breach databases, and news archives to produce detailed targeting dossiers at scale. Gray (2021) demonstrates that photograph EXIF metadata alone can yield GPS coordinates, device model, and operating system information. The normalization of remote work and proliferation of IoT devices have further expanded the attack surface: home networks lack enterprise-grade segmentation, and IoT devices run on weak default credentials (Gururaj et al., 2024).

7. Case Studies

7.1 The 2011 RSA SecurID Breach

In March 2011, RSA Security was breached through a single phishing email with the subject line "2011 Recruitment Plan.xls." The attachment exploited a then-unpatched Adobe Flash zero-day. Three psychological mechanisms were engaged simultaneously: relevance (recruitment information was professionally salient), credibility (the apparent sender was plausible), and curiosity (a salary spreadsheet implied actionable information). The Remote Access Trojan installed through that single interaction gave attackers access to SecurID seed values subsequently used to compromise Lockheed Martin and other defense contractors. One employee's momentary decision cascaded into a national security incident (Hadnagy, 2011; Sonowal, 2023).

7.2 The 2020 Twitter Bitcoin Scam

In July 2020, attackers compromised Twitter's internal administrative tools without exploiting a single technical vulnerability. Access was obtained entirely through a coordinated phishing campaign: the attackers impersonated internal IT staff, directed targets to a fake VPN portal, and collected credentials through a process that looked operationally normal to the employees. With administrative access, they hijacked verified accounts of Barack Obama, Joe Biden, Elon Musk, Bill Gates, and Apple, running a Bitcoin scam returning approximately \$120,000 in under thirty minutes (Sonowal, 2023). The case is important precisely because Twitter's technical security was adequate; the attack succeeded because technical security cannot protect against threats operating through the authorized humans who administer it.

7.3 The \$25 Million Hong Kong Deepfake Fraud (2024)

The February 2024 Hong Kong case represents a step-change in financial scale and technological sophistication. A finance employee authorized transfers totaling approximately HK\$200 million after participating in a video conference in which every other participant was an AI-generated deepfake of real senior executives. The employee became suspicious only after contacting the real individuals through a separate channel, by which point all transfers had been executed. Hong Kong police confirmed this as the first publicly documented case of multiple deepfake personas deployed simultaneously in a real-time interactive fraud (Gururaj et al., 2024).

8. An Integrated Defense Framework

Social engineering cannot be addressed by any single countermeasure. The attacks operate across technical, psychological, procedural, and physical dimensions simultaneously. The framework proposed below synthesizes recommendations from Gray (2021), Sonowal (2023), Hadnagy (2011), and Gururaj et al. (2024) into three interlocking components.

8.1 Technical Controls

Email authentication infrastructure offers the highest technical leverage against phishing. Gray (2021) presents the SPF, DKIM, and DMARC protocol stack as the foundational layer; organizations deploying DMARC at enforcement level ($p=reject$) effectively eliminate domain spoofing as a viable attack vector. Hardware security keys implementing FIDO2/WebAuthn provide the strongest MFA protection because they are physically bound to the authentication session and cannot be relayed by adversary-in-the-middle attacks. Gururaj et al. (2024) recommend AI-powered behavioral analytics capable of flagging anomalous communication patterns and synthetic audio signatures. Zero Trust architecture requires continuous verification of every access request regardless of origin.

8.2 Human-Centered Defense

Gray (2021) draws a sharp distinction between compliance-oriented training — the annual awareness module satisfying a regulatory checkbox — and engagement-oriented programs that develop actual threat recognition capability. Programs producing measurable outcomes: run continuously rather than annually; maintain a non-punitive culture (Gray, 2021, p. 21, explicitly argues that public identification of employees who fail simulated attacks suppresses incident reporting and destroys the psychological safety effective defense requires); use behavioral simulation rather than passive knowledge transfer; differentiate content by role; and update continuously to address AI-generated lures.

The core behavioral defense that Hadnagy (2011), Gray (2021), and Sonowal (2023) converge on is verify out-of-band. Any request for a sensitive action — a wire transfer, a credential reset, a grant of system access — must be confirmed through a separate, pre-established communication channel before it is executed. This single practice, applied consistently, neutralizes even the most technically sophisticated attacks. The 2024 Hong Kong deepfake fraud would have been stopped at this step.

8.3 Organizational Governance and Culture

Sonowal (2023) identifies three primary governance domains requiring explicit policy: internet usage, email security, and physical access. Critical elements include authorization procedures for sensitive transactions that cannot be bypassed regardless of the apparent seniority of the requester; least-privilege access controls; and clear, non-punitive escalation procedures. Gururaj et al. (2024) identify unclear reporting structures as a significant

organizational vulnerability: an employee who suspects manipulation but fears blame will delay or avoid reporting, collapsing the response window.

All three pillars rest on organizational culture. Gray (2021), Hadnagy (2011), and Gururaj et al. (2024) reach consistent conclusions: the strongest single predictor of social engineering resilience is whether employees genuinely feel safe to report suspicious contacts and challenge apparent authority. Edmondson's (1999) research on psychological safety provides the theoretical support: organizations with high psychological safety detect errors faster and develop more durable competence over time.

9. Discussion

The most consequential strategic implication of AI-augmented social engineering is that the dominant model of security awareness training is structurally obsolete. Programs built around teaching employees to recognize surface-level anomalies were designed for a threat environment that no longer exists. A large language model prompted with a target's public professional profile can produce a spear-phishing message that clears every heuristic a trained employee has been taught to apply. Training people to detect AI-generated content is not a viable alternative; the necessary reorientation is from message-level detection to process-level verification.

The culture finding carries its own strategic implication. Edmondson's (1999) psychological safety research shows that organizations where people feel safe to admit mistakes and report concerns detect incidents earlier and recover more effectively. Organizations that treat every failed phishing simulation as a performance failure produce a workforce that conceals incidents rather than reporting them. Measurement frameworks for security awareness programs need to track reporting rates alongside failure rates. Legal and regulatory frameworks have not kept pace with the threat; Sonowal (2023) finds that the psychological manipulation component of social engineering frequently falls into legal grey areas until material harm has already occurred.

10. Limitations

As a systematic narrative review rather than an empirical study, this paper's conclusions depend on the quality and representativeness of the source material. The four primary texts do not represent the full breadth of the social engineering literature, particularly work published in non-English languages. The case studies are limited to three publicly documented incidents; the full population of social engineering attacks is substantially larger and includes many incidents that are never publicly disclosed. Empirical data are drawn from self-reported incident databases and vendor-sponsored research, both of which have well-documented biases. The AI-threat analysis is based on publicly disclosed incidents as of early 2025; specific capability threshold claims may require updating.

11. Future Research Directions

Longitudinal empirical studies comparing compliance-oriented and engagement-oriented security awareness training against documented incident rates are needed to move the field from practitioner intuition to evidence-based program design. The psychological safety and security culture relationship identified by Edmondson (1999) has not been tested empirically in organizational cybersecurity contexts. The AI threat landscape requires dedicated empirical work: the 2024 Hong Kong deepfake fraud is currently the most thoroughly documented multi-participant synthetic media attack, but systematic incident

analysis across a larger population of AI-augmented cases does not yet exist. A comparative legal analysis of how existing criminal and civil frameworks apply to the manipulation techniques used in social engineering would provide a foundation for the regulatory evolution the field clearly needs (Sonowal, 2023).

12. Conclusions

Social engineering is the oldest attack method on record, and artificial intelligence has made it more effective than it has ever been. Its persistence across every era comes down to a structural reality: every technical system is ultimately operated by human beings whose cognition is built around trust, cooperation, and responsiveness to authority. Those tendencies are not vulnerabilities in the engineering sense; they are the foundations of functional social life. The question is not whether they can be removed but whether organizations can build systems and cultures that make them harder to exploit systematically.

This paper has made three substantive contributions. First, it identified a gap in the existing literature: no prior synthesis addresses the intersection of behavioral psychology, an updated attack taxonomy including AI-augmented vectors, and a defense framework designed for the current threat environment. Second, it proposed a defense-in-depth framework that treats technical controls, human-centered training, and organizational governance as co-equal components, with organizational culture as the foundation that determines whether the other components function as intended. Third, it traced the AI escalation through documented incidents to establish that the shift from theoretical threat to operational reality has already occurred. As Hadnagy (2011, p. 8) put it, the bad guys do not stop because of a contractual limitation or their own morals. The only proportionate response is a commitment to understanding, learning, and building human resilience that is equally persistent and equally unconstrained.

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Why We Need New Access Models: From Session-Bound Authorization to Continuous Access

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Abstract. This article shows why existing security approaches and access-control models no longer meet the requirements of today's digital environment, and what next-generation models should incorporate to close the resulting gap. We briefly review classical models (DAC/MAC, RBAC, ABAC, etc.) and identify where they fall short amid highly dynamic context, cross-organizational workflows, and compressed decision-making cycles. On this basis, we articulate requirements for next-generation models: continuous, context-adaptive authorization; explicit treatment of risk and trust; machine-readable and verifiable policies; and traceable delegation with revocation. Practical examples illustrate the applicability of several models, along with their limitations and risks (e.g., staleness of contextual attributes, increased administrative complexity, reduced explainability). Our central thesis is a shift from replacement to composition: classical mechanisms retain their value as a stable foundation, while new prototypes are layered on top to close gaps without sacrificing manageability. The article offers practical guidance for designing and evolving access-control systems and security policies in modern organizations.

Keywords. Access control; dynamic context; risk-adaptive authorization; model composition; security policy.

1. Introduction

Over the past half century of access control, the IT industry has moved from simple permission matrices to mature enterprise systems based on roles and attributes. These solutions shaped the security vocabulary (subject, object, operation), delivered manageability and regulatory compliance, and enabled policy portability across systems [1], [6], [7], [8]. However, computing architectures have changed radically: data resides in clouds and on edge devices; organizations operate across domain and jurisdictional boundaries; employees move between networks and applications; and the “last mile”—the moment when information is rendered to a human—has become a vulnerability in its own right.

In this setting, traditional session-bound authorization (“check once—allow until the session expires”) is no longer adequate. A new class of models is needed in which the access decision is not fixed but is maintained and revised throughout the entire interaction with the data; in which the object itself remains encrypted until policy conditions are satisfied; and in which relationships among participants are as important as their statuses [9], [10], [12]–[14]. The goal of this paper is to show why existing approaches no longer meet modern requirements and what new models can introduce to close the gap. We draw on established paradigms (DAC/MAC, RBAC, ABAC/UCON, Zero Trust, ReBAC) and compare them with the challenges of distributed infrastructures, interorganizational cooperation, and last-mile exposure [1], [4]–[12].

2. Historical Foundations

Early Foundations: Protection Matrix and Capabilities

The first formalizations described the world simply: subjects and objects whose relationships are recorded in a matrix, and a process that carries with it a set of capabilities—roughly, tokens marking the right to perform a given operation [3]. This era gave us the language and mechanics we still use today: subject/object/operation, the representation of rights as data, and the idea of delegation. But as systems grew, it became clear that a flat matrix balloons too quickly, and managing delegations becomes no less complex than the business processes themselves [1], [3].

Two Streams of the 1970s–1990s: Discretionary and Mandatory

The mass-market IT answer to the question “who is the owner?” was Discretionary Access Control (DAC): the object owner decides who can do what; thus the familiar ACLs, groups, and the UNIX/Windows “file owner” emerged. This is flexible and administrator-friendly but vulnerable to Trojan-horse attacks and hard to oversee at scale [1]. In parallel, the military-industrial domain insisted on a different logic—Mandatory Access Control (MAC): secrecy labels and formally provable information-flow constraints (Bell–LaPadula lattices for confidentiality and Biba for integrity) [4], [5]. MAC makes leakage “mathematically hard,” but fits poorly with open collaboration and the everyday fluidity of access.

1990s–2000s: Manageability through Roles

The corporate IT revolution created the need to manage functions rather than individual permissions. RBAC took shape accordingly: roles aggregate permissions; users are assigned roles; and separation of duties, role administration, and an ANSI standard followed [6]. RBAC delivered manageability and audit compliance, but encountered a “role explosion” across diverse business cases, where hundreds of nuances turned the role table into a new matrix.

2000s–2010s: Expressiveness through Attributes and Usage Control

The focus shifted from “who you are” to “what is known about you and what the context is.” ABAC (and the XACML ecosystem) allowed policies to be expressed as predicates over subject, object, and environment attributes, while separating the Policy Decision Point (PDP) from Policy Enforcement Points (PEP) [7], [8]. This increased expressiveness but raised questions about attribute provenance and quality, as well as testability and explainability. A further step was UCON: access as use under a set of obligations and conditions, with attributes changing on the fly [9]. Access ceased to be a “flick of a switch” and became a process dependent on the fulfillment of obligations and the dynamics of context.

2010s–2020s: Zero Trust, Relationship Graphs, and the Vanishing Perimeter

Mobility, SaaS, and microservices eroded the notion of a “trusted inside.” Zero Trust Architecture prescribed revalidating every request, microsegmenting access, and treating the network as hostile by default [10]. In collaborative products, another regularity emerged: permissions are naturally derived from relationships—“workspace member,” “folder editor,” “delegated by X.” This led to system-scale implementations of ReBAC (relationship-based access control), where a global authorization graph becomes the primary source of truth [12]. The efficiency gains are dramatic: instead of hundreds of role combinations, a small set of edge types and path checks suffices.

3. Brief Context: What Classical Models Solved

Discretionary and mandatory access control were developed under different design logics: DAC grants the object owner the authority to decide “who can do what,” providing convenience and flexibility; MAC applies secrecy/integrity labels and enforces formally provable information-flow restrictions, which critical systems require [1], [4], [5]. The corporate era introduced RBAC—roles as a “container” of permissions and manageability at enterprise scale [6]. As access scenarios grew more complex, attribute-based policies (ABAC) and the separation of Policy Decision Points (PDP) from Policy Enforcement Points (PEP) emerged—greater expressiveness and centralized policy control with distributed enforcement [7], [8]. In parallel, the idea of Usage Control (UCON) evolved: authorization is not a one-time admission check but a process tied to obligations and conditions that may change on the fly [9]. As the network “perimeter” ceased to be a reliable boundary, the Zero Trust paradigm appeared: trust neither networks nor hosts by default; verify each request [10]. In highly collaborative systems, relationships moved to the forefront—who participates in which space, who delegated to whom—and permissions are derived from a relationship graph (ReBAC) [12]. Each paradigm addressed the problems of its time and remains valuable within its scope. Today’s environment, however, imposes three classes of requirements that exceed those boundaries.

4. Where Current Approaches Fall Short

First, contextual dynamics. The “static session” has given way to a stream of events: a device switches networks, behavioral risk rises, biometric “liveness” drops out. Permission granted in the morning may be unsafe by midday. Session-bound authorization cannot loosen its grip as conditions change, and classical extensions (hidden timeouts, idle thresholds) are merely surrogates for true contextual dynamics [9], [10]. Second, interorganizational relationships. Projects now bring together people and services from different legal entities, domains, and cloud tenants. Role models designed for a single organization lead to role explosion and exceptions, while attribute-based models complicate the issuance and verification of attributes for external participants. In practice, rights are often determined by relationships (participation, ownership, delegation), which are naturally expressed as a graph rather than flat lists [12]. Third, perimeter dissolution and last-mile vulnerability. Data are copied, cached, and flow to endpoints and third-party clouds. Even perfect server-side authorization is insufficient if an object appears in plaintext on the wrong screen: shoulder-surfing, a compromised OS, or screen recording can all slip past policy. Traditional access models do not even perceive the moment of display and cannot manage it as part of access control.

5. What New Models Must Provide

1). Continuity and risk adaptiveness. Access is not an entry pass but a state maintained as long as context remains within the risk policy. The authorization decision can be revised at any moment: if verified user presence ceases, access collapses; if the connection shifts to an unsafe network, permissions automatically narrow. This requires embedding—mechanically and semantically—the notions of revocation and controlled “weakening” of access in response to risk signals [9], [10].

2). “Data-as-controller”. An object must be able to withhold disclosure unless conditions are met. This is achieved by moving part of the control into the data: attribute-/factor-dependent encryption (including biometrics) and policies defined at the object level.

Until the predicate holds, it remains ciphertext; once satisfied, decryption occurs locally for the minimum necessary time [13], [14].

3). Relationship semantics. Actual permissions are determined by who is related to whom and how. The model must derive permissions from a relationship graph (space member, co-owner, delegate) and validate them with guaranteed consistency at scale [12]. This reduces administration and reflects collaboration better than role combinatorics.

4). Display control as part of access. The last mile cannot remain outside policy: where and how plaintext is rendered, to whom, and through which channel. One-way, personal output channels (e.g., a standalone wearable without network interfaces that locally decodes ciphertext) are critical, as is binding verified “live presence” to the very permission to display [10], [15].

5). Revocability and replaceability of bindings. Compromising auxiliary data should not permanently compromise the biometric or require changing the object - reissuing the binding suffices. The cryptographic layer must be replaceable (crypto-agile): policy is independent of specific primitives and can withstand transition to post-quantum schemes [13], [14].

6. Illustrations of the Requirements in Typical Scenarios

Distributed analytics scenario. A team from three companies prepares a joint report. Data are replicated across clouds, and participants come and go. Role-based models within individual organizations produce a “combinatorial explosion” of roles and delegations; attribute-based models provoke disputes over who issued attributes and how they expire. A relationship graph expresses participation and delegation; “data-as-controller” ensures that a downloaded report remains ciphertext outside the project context; continuity enables automatic removal of rights as soon as a participant leaves the project [7], [10], [12], [13].

Mobile access to sensitive data scenario. An employee reads a document at an airport. One-time authorization at 9:00 a.m. does not account for the fact that at 9:05 a.m. he joined an unfamiliar open network, and at 9:07 a.m. people gathered around him. Continuous control lowers the access level when the network changes; “last-mile” protection blocks display without a personal decoder device; the object remains ciphertext on a shared PC screen [9], [10].

“Time-bound delegation” scenario. A manager goes on vacation and temporarily delegates access to a folder with contracts to an assistant. Role-based assignment of permissions risks being forgotten later. The relationship graph encodes delegation with an automatically expiring edge; “data-as-controller” will not reveal itself to the assistant unless contextual conditions (location, device) are met [12], [13].

In each example, the object is encrypted under stated conditions, relationships are explicitly expressed and verified, and the access decision is not one-off but sustained.

7. Manageability and Explainability

New models are often criticized as “black boxes.” That critique is appropriate when policies are scattered across systems. Properly organized, however, they improve explainability: policy is expressed as code (policy-as-code); a single source of truth is versioned and tested; the relationship graph provides verifiable paths; and cryptographic binding yields an unambiguous condition for why decryption occurred. For audit, this is even more convenient than disparate ACLs and exotic roles [7], [11], [12], [13].

It is also important that the new principles are compatible with existing ones: RBAC remains a convenient “add-on” as manageability layer, ABAC provides expressive condition

logic, and Zero Trust enforces network-level discipline. This is not a replacement but a composition.

8. Limitations and Risks to Keep in Mind

First, the hygiene of attributes and relationships is critical: who issues them, how long they remain valid, and how they are revoked. Without disciplined provenance, attribute-based policies become a source of errors [7].

Second, privacy. Any solution that uses biometric factors must guarantee the revocability of bindings and the non-reconstructability of biometrics from auxiliary data; fuzzy extractors address exactly this requirement [14].

Third, post-quantum resilience. If control is pushed into the cryptographic layer, the system must allow primitives to be replaced without rewriting policies. This argues for clear layering: policy separate from cryptography [13].

Finally, “last mile engineering is required”. Personal display devices should be widely available and manageable. The market for wearable glasses and AR devices is evolving rapidly, which makes this aspect practically achievable [2].

9. What Is Relevant Today

Some of the ideas described are already being implemented in products: global authorization services built on relationship graphs (inspired by industrial-grade systems like Zanzibar), centralized attribute-based policy engines, and “Zero Trust” as a discipline of re-verifying each request [10], [12]. Policy-as-code engineering practices are taking root in secure development, enabling policies to be tested and explained [7], [11]. Cryptographic “data-as-controller” approaches are being actively researched and deployed in niche scenarios (attribute-based encryption, confidential containers) [13]. Against this backdrop, a natural next step is to bind access to “live” factors - including biometric ones - with guaranteed revocability, and to govern the visualization itself as part of policy [14], [15], [2].

10. Conclusion

Traditional access-control models brought order in an era of centralized systems and stable roles. But where data are distributed, participants are linked by flexible relationships, and the threat shifts to the moment of display, session-bound (“one-time”) authorization stops working. New models must do three things: (1) turn access from an event into a continuous state with revocation driven by risk signals; (2) move part of the control into the object so that it does not disclose outside the required conditions; and (3) treat relationships as the primary source of meaning for authority. These principles do not replace RBAC and ABAC; they compose with them into a coherent architecture.

This perspective opens the way to practices in which the human, their relationships, and the data themselves form a single security framework. On this foundation, further development is possible—even solutions in which an encrypted document “lives” inside a biometrically bound carrier and is displayed only through a personal, one-way channel. New access models are needed not “for fashion’s sake,” but because they are the only ones capable of faithfully accounting for contextual dynamics, perimeter dissolution, and last-mile vulnerability - without sacrificing manageability and explainability [1], [7], [10], [12]–[14].

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Global Trends in Intellectual Property in 2023–2024

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Abstract. This article examines global trends in the field of intellectual property (IP) based on statistical data published by the World Intellectual Property Organization (WIPO), including the reports IP Facts and Figures 2024-2025 and World Intellectual Property Indicators 2024-2025. The study analyzes application dynamics across patents, utility models, trademarks, and industrial designs, focusing on developments in 2023–2024. Particular attention is paid to regional distribution patterns, application intensity relative to GDP, sectoral specialization, and the increasing role of middle-income countries in the global IP system. The analysis reveals continued growth in intellectual property activity, particularly in Asian economies, as well as a gradual increase in the share of resident filings in developing jurisdictions. The findings also indicate a structural shift toward technology- and design-intensive sectors and an expanding role of intellectual property indicators in assessing innovation performance. By combining statistical analysis with a policy-oriented perspective, the article provides an updated view of global intellectual property dynamics and discusses their implications for the development of national IP strategies. Particular attention is given to the role of institutional incentives, sectoral priorities, and the integration of IP statistics into economic and innovation policymaking.

Keywords. Intellectual property, WIPO, patents, trademarks, utility models, industrial designs, IP statistics, innovation policy, GDP, middle-income countries

1. Introduction

The contemporary knowledge-based economy predetermines intellectual property (IP) rights as one of the key resources for the technological and social development of modern society. Having acquired the status of a strategic asset, intellectual property is increasingly moving beyond the boundaries of the purely legal sphere and is becoming a central element of the innovation, industrial, and digital policies of modern states.

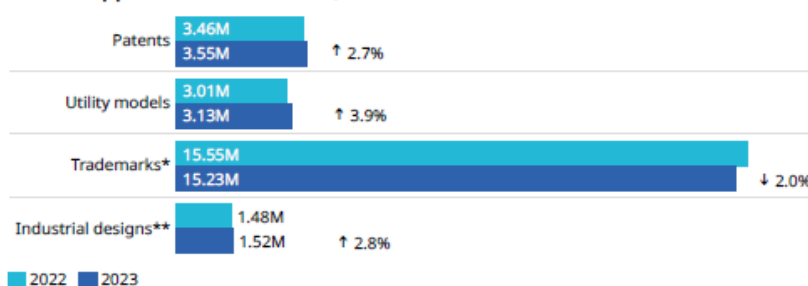
The analysis of global statistical data published by the World Intellectual Property Organization (WIPO)[1], including the reports IP and Facts 2024[2], IP Facts and Figures 2025 [3], World Intellectual Property Indicators 2024[4] and World Intellectual Property Indicators 2025[5], provides a unique opportunity to identify the key directions in the transformation of the global system for the protection of intellectual property rights. The focus of this study is not limited to quantitative changes in the main categories of industrial property rights, but also includes their regional distribution, the structure of sectoral demand, as well as the intensity of filing activity in relation to the economic potential of different countries.

Despite the availability of extensive international statistics on intellectual property, a systematic interpretation of recent global filing trends and their policy implications remains relatively limited in the academic literature. This article seeks to contribute to this discussion by providing an integrated analysis of key statistical indicators and emerging structural shifts in global intellectual property activity.

2. Global Trends in Intellectual Property Activity (2023–2024)

A detailed analysis of global filing activity in 2023 indicates that the international system of industrial property demonstrated positive dynamics across most key categories of intellectual property rights. According to WIPO data[1], the number of patent applications increased by 2.7%, utility model applications by 3.9%, and industrial design applications by 2.8%. At the same time, the number of trademark applications declined by approximately 2% compared with the previous year. Nevertheless, the overall volume of filings remained consistently high, reaching around 15.2 million trademark applications, 3.6 million patent applications, and approximately 1.5 million industrial design applications worldwide.

1. Total applications worldwide, 2023



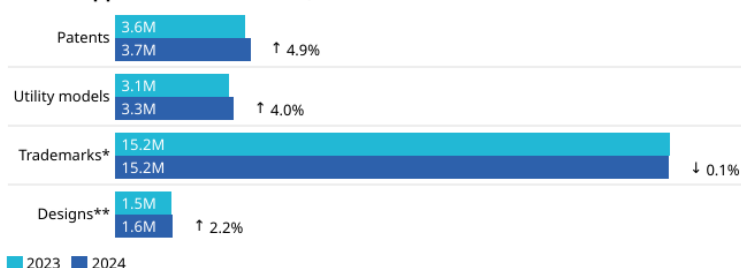
Notes: * refers to class count – the total number of goods and services classes specified in trademark applications. ** refers to design count – the total number of designs contained in industrial design applications.

Source: WIPO Statistics Database, August 2024.

Fig. 1. Total applications worldwide, 2023.

Data for 2024 confirm the continuation of these trends. According to the WIPO report World Intellectual Property Indicators 2025 [5], the global number of patent applications reached approximately 3.7 million, representing an increase of 4.9% compared with 2023. Positive dynamics were also observed for utility models (+4.0%) and industrial designs (+2.2%). At the same time, trademark filing activity remained largely stable, showing only a slight decline of around 0.1%.

1. Total applications worldwide, 2024



Notes: * refers to class count – the total number of goods and services classes specified in trademark applications. ** refers to design count – the total number of designs contained in applications.

Source: WIPO Statistics Database, September 2025.

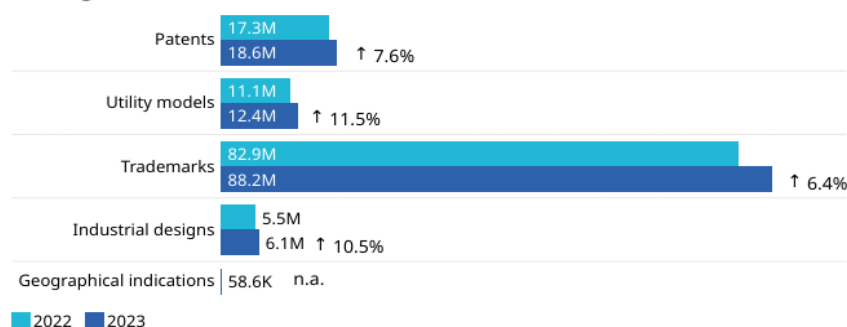
Fig. 2. Total applications worldwide, 2024.

The decrease in trademark activity may be interpreted as reflecting broader macroeconomic uncertainty, which primarily affects sectors associated with consumer markets, branding, and marketing activities. At the same time, the growth in patent and utility model filings indicates the continued strategic focus of companies on the protection of technological solutions and technical innovations.

Thus, despite short-term fluctuations across individual categories of intellectual property rights, the global intellectual property system as a whole continues to demonstrate steady growth in filing activity, reflecting the increasing importance of intangible assets in the modern global economy.

An equally indicative trend is the growing number of active intellectual property rights worldwide. In particular in 2023, the total number of active trademark registrations reached 88.2 million (+6.4%), while the number of registered industrial designs amounted to 6.1 million (+10.5%) and active patents totaled approximately 18.6 million (+7.6%).

3. IP rights in force, 2023

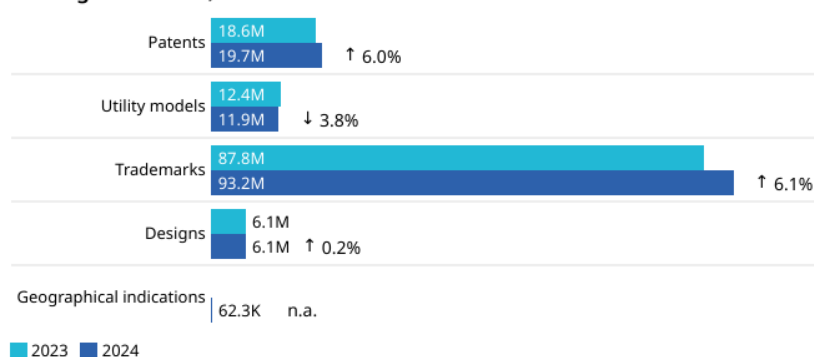


Note: n.a. indicates not available.

Source: WIPO Statistics Database, August 2024.

Fig. 3. IP rights in force, 2023

3. IP rights in force, 2024



n.a. indicates not available.

Source: WIPO Statistics Database, September 2025.

Fig. 4. IP rights in force, 2024

The analysis of statistical data for 2024 [2,4] makes it possible to assess the structure and dynamics of the global stock of intellectual property rights in force. The most widespread

form of intellectual property protection continues to be trademarks, with the total number of active registrations reaching approximately 93.2 million, representing an increase of 6.1% compared with 2023.

The number of patents in force also continued to grow, increasing from 18.6 million in 2023 to approximately 19.7 million in 2024, which corresponds to a rise of about 6.0%. At the same time, the total number of industrial designs in force remained largely stable at around 6.1 million, showing only a marginal increase of about 0.2%.

A somewhat different dynamic can be observed with respect to utility models. Despite their considerable scale, the global stock of active utility model rights declined from 12.4 million to 11.9 million, representing a decrease of approximately 3.8%.

Overall, these figures indicate the continued expansion of the global portfolio of protected intellectual property assets. The dominance of trademarks reflects their role as the most widely used instrument of market differentiation, while the steady growth in patents confirms the sustained importance of technological innovation in the contemporary global economy. These indicators confirm that, despite short-term fluctuations in filing activity, the overall volume of protected intellectual property assets continues to grow.

Thus, a dual trend can be observed. On the one hand, companies appear to be optimizing expenditures related to brand promotion and trademark protection, which is reflected in the relative stabilization of trademark filings. On the other hand, businesses continue to strengthen their positions in technological and production-oriented sectors through patent protection and related instruments of industrial property. This also reflects a gradual shift toward the growing importance of the “invisible” value of assets — technologies, design solutions, and innovative technical developments.

In this context, it becomes relevant to examine how these trends are reflected in the global geographical distribution and regional concentration of intellectual property activity.

3. Regional concentration and distribution of intellectual property activity

The geographical distribution of intellectual property filings demonstrates a pronounced regional concentration of innovation activity. According to WIPO data [1], a significant share of global intellectual property filings is concentrated in Asia. In 2023, applications filed with offices in the Asian region accounted for 68.7% of all patent applications, 69% of trademark applications, 66.7% of industrial design applications, and almost 99% of utility model filings [2].

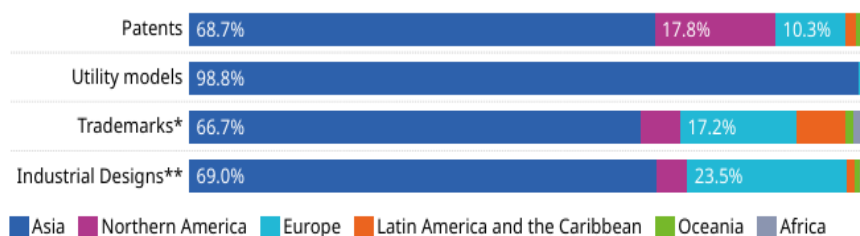
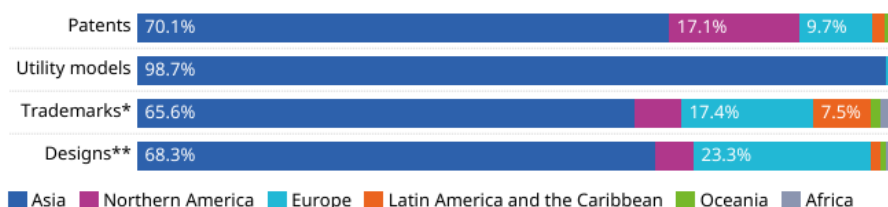


Fig. 5. Information for regional concentration and distribution of intellectual property activity

Data for 2024 confirm the persistence of this pattern. As illustrated, Asia continues to dominate global intellectual property activity[4].

2. Percentage shares of IP filing activity by region, 2024



Notes: * refers to class count – the total number of goods and services classes specified in trademark applications. ** refers to design count – the total number of designs contained in applications. Northern American offices do not offer utility model registration and therefore are not included in the bar for that particular IP right.

Source: WIPO Statistics Database, September 2025.

Fig. 6. Percentage shares of IP filing activity by region, 2024.

In 2024, offices in the region accounted for approximately 70.1% of global patent applications, 65.6% of trademark filings, and 68.3% of industrial design applications. The concentration is even more pronounced in the case of utility models, where the share of Asian offices reached 98.7%, reflecting the particularly widespread use of this form of protection in several Asian jurisdictions.

This concentration reflects the rapid development of technological and industrial capacities in a number of Asian economies, as well as the increasing role of the region in the global innovation system. The scale of filing activity indicates that Asia has become the primary center of global intellectual property activity, particularly in sectors related to manufacturing, applied technologies, and product design.

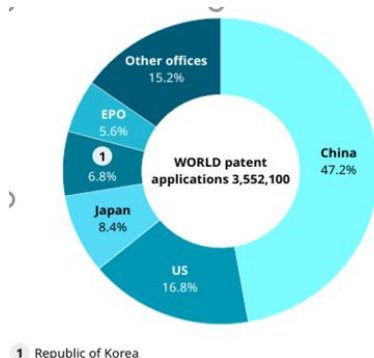
At the same time, North America and Europe continue to maintain strong positions in the field of high-technology innovation and research-intensive industries. In 2024, North America accounted for about 17.1% of patent filings, while Europe represented approximately 9.7% [6]. In the case of trademarks and industrial designs, Europe demonstrates a somewhat larger share, reflecting the strong role of European markets in brand protection and product design.

Other regions - including Latin America and the Caribbean, Oceania, and Africa - account for comparatively smaller proportions of global intellectual property filings. Nevertheless, their participation indicates the gradual expansion of innovation activity beyond the traditional centers of technological development.

Nevertheless, the overall structure of global filing activity remains highly concentrated, which highlights the dominant role of East Asian economies - primarily China, the Republic of Korea, and Japan — in the contemporary architecture of the global intellectual property system.

Data for 2023 indicate a high concentration of filing activity within a limited number of leading intellectual property offices. This pattern largely reflects the dominant role of East Asian economies - primarily China, the Republic of Korea, and Japan — in the contemporary architecture of the global intellectual property system. China continues to play a leading role in these processes. In 2023, the Chinese patent office accounted for approximately 47.2% of all patent applications worldwide, more than 54% of industrial design filings, and nearly half of all trademark applications. Notably, the vast majority of these applications are filed by Chinese residents, which reflects not only the technological maturity of the Chinese economy but also a high level of institutional trust in the national intellectual property protection system. The Republic of Korea and Japan also maintain consistently strong positions in global patent

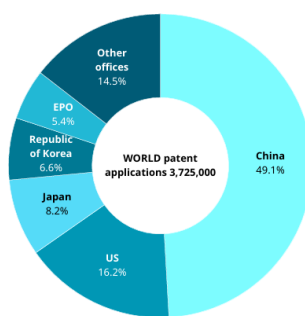
activity. At the same time, the relative shares of the United States and the European Patent Office in the global distribution of patent filings have gradually declined over the past decade. In particular, the share of the United States decreased from approximately 22.3% of global patent applications ten years ago to about 16.8%, while the share of the European Patent Office fell to around 5.6% [6]. This trend may reflect both the relative maturity and saturation of innovation systems in advanced economies and the growing competitive pressure from countries demonstrating higher filing intensity and rapidly expanding technological capabilities.



Note: EPO is the European Patent Office.

Fig. 7. World patent applications, 2023

Data for 2024 confirm the persistence of this trend. According to WIPO statistics, the five largest offices - China, the United States, Japan, the Republic of Korea, and the European Patent Office - together accounted for approximately 85.5% of all patent applications filed worldwide[3, 5].



Note: EPO is the European Patent Office.
Source: WIPO Statistics Database, September 2025.

Fig. 8. World patent applications, 2024

China remains the clear leader, accounting for approximately 49.1% of global patent applications, meaning that nearly every second patent application worldwide is filed in China[7]. The United States accounted for about 16.2% of global patent filings, followed by Japan (8.2%) and the Republic of Korea (6.6%), which continue to hold strong positions within the global innovation system. The share of the European Patent Office amounted to approximately 5.4%[6]. These further confirm the longer-term trend discussed above, namely the gradual decline in the relative shares of the United States and the European Patent Office in the global distribution of patent filings.

At the same time, the growing concentration of patenting activity among the largest offices has been driven largely by the rapid expansion of patent filings in China. Over the past decade, China's share of global patent applications increased from 34.6% in 2014 to 49.1% in 2024, reflecting the accelerating development of the country's technological and innovation capacity[7]. Thus, the analysis of WIPO statistics indicates a dual concentration of global intellectual property activity. On the one hand, a significant share of global filings is concentrated in Asia, which accounts for around 70% of patent applications worldwide. On the other hand, the majority of patent activity is concentrated in a small group of leading intellectual property offices, which together receive more than 85% of all global filings.

Taken together, these developments indicate a structural shift in the global geography of innovation, with the center of patenting activity increasingly concentrated in East Asia, and particularly in China. Amid these developments, countries with emerging innovation ecosystems are demonstrating increasing activity. In particular, India recorded a 15.7% increase in patent applications in 2023, marking the fifth consecutive year of double-digit growth [2].

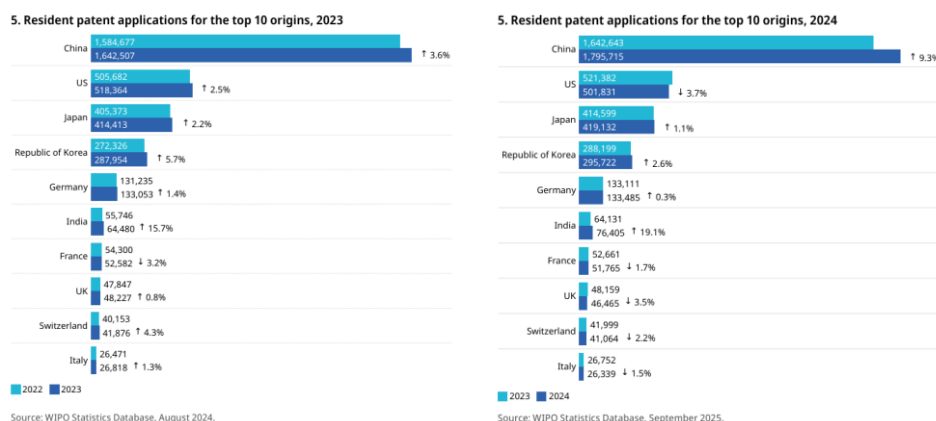


Fig. 9. Resident patents application for the top 10 origins, 2023 and 2024

Data for 2024 further confirm this trend. As illustrated, India increased the number of patent applications to approximately 76.4 thousand, representing a 19.1% increase compared with the previous year. This dynamic indicates that the country is gradually strengthening its position among the major sources of patent applications worldwide and is becoming one of the most rapidly expanding innovation actors.

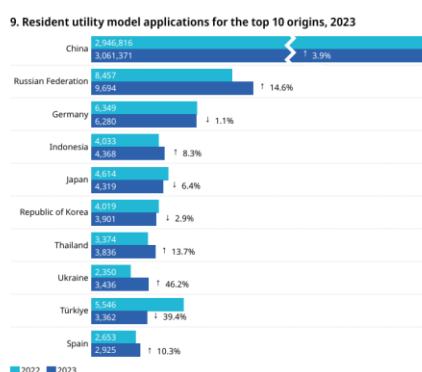
At the same time, the dynamics of patent activity among leading countries remain uneven. China continues to demonstrate strong growth (+9.3%), while the United States recorded a moderate decline (–3.7%). Meanwhile, Japan and the Republic of Korea maintain relatively stable growth (+1.1% and +2.6%, respectively), reflecting the resilience of their national innovation systems. Similar patterns can also be observed in the field of utility model applications, which often serve as a more accessible instrument for protecting technical solutions in developing innovation systems. At the same time, a comparable increase in filing activity in 2023 can be observed in several emerging economies — including Turkey, Viet Nam, Brazil and Ukraine — particularly in the segments of trademarks and industrial designs.

Presented illustrate the distribution of resident utility model applications among the top origins in 2024. As in previous years, China remains the dominant actor in this category, with more than 3.18 million applications, demonstrating a further increase of 4.0% compared with 2023. At the same time, several countries demonstrate particularly notable growth in

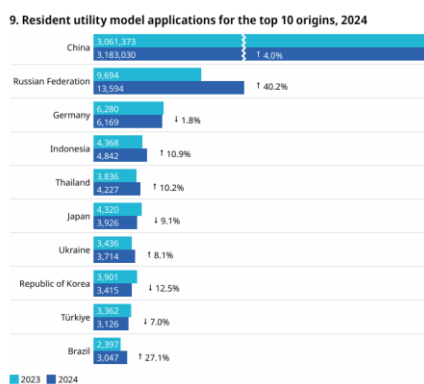
utility model filings. The most significant increase is observed in the Russian Federation, where the number of applications rose by 40.2%, reaching approximately 13.6 thousand. A substantial rise is also recorded in Brazil (+27.1%), while Indonesia (+10.9%) and Thailand (+10.2%) show steady growth in the use of this form of protection. Moderate increases are observed in Ukraine (+8.1%), while Türkiye demonstrates a slight decline (–7.0%). At the same time, a decrease in filings is recorded in Japan (–9.1%) and the Republic of Korea (–12.5%), whereas Germany remains relatively stable (–1.8%).

Overall, these s suggest that the use of utility models continues to expand in several emerging innovation systems, where this instrument often serves as a more accessible mechanism for protecting incremental technical solutions.

Thus, the regional shift toward Asia is becoming a stable structural feature of the global intellectual property system. At the same time, the contribution of developing economies to global filing activity continues to grow. This trend creates new challenges for the global harmonization of intellectual property protection standards and highlights the need to take regional specificities into account in the development of international intellectual property policy.



Source: WIPO Statistics Database, August 2024.



Source: WIPO Statistics Database, September 2025.

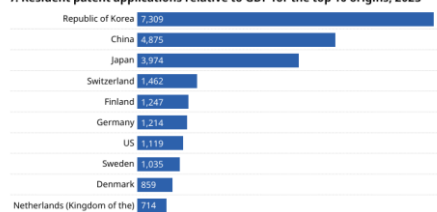
4. Filing intensity relative to GDP

In addition to absolute filing volumes, an important indicator of the maturity of national intellectual property systems is the intensity of filings relative to gross domestic product (GDP)[9]. This metric makes it possible to compare countries with different economic sizes and to identify the relative level of engagement in the creation and protection of intellectual property [10]. According to WIPO statistics, in 2023 the Republic of Korea ranked first in terms of resident patent applications per USD 100 billion of GDP, with 7,309 applications. The second and third positions were occupied by China (4,875) and Japan (3,974). Notably, Finland, surpassing Germany, entered the top five for the first time with 1,247 applications per USD 100 billion of GDP, reflecting a strong concentration of research and development resources [4].

Data for 2024 indicate certain shifts in the distribution of leading countries. China recorded the highest intensity of patent filings with 4,977 applications per USD 100 billion of GDP, followed by Japan (4,150). Among European economies, Switzerland (1,506), Finland (1,331) and Germany (1,241) demonstrate relatively high patent filing intensity, reflecting the strong role of research-intensive and technology-driven sectors in their economies.

A similar analysis for trademarks reveals a somewhat different structure of filing intensity. In 2024, China remains the leading country with 20,198 classes per USD 100 billion of GDP, followed by Türkiye (12,144), Brazil (10,226) and the Russian Federation (8,599). Several smaller economies, including Chile, also show relatively high filing intensity, reflecting the active development of domestic markets and entrepreneurial activity:

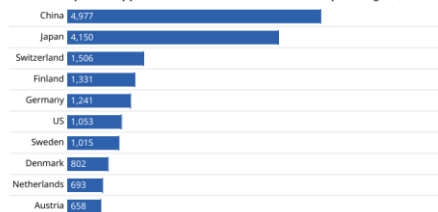
7. Resident patent applications relative to GDP for the top 10 origins, 2023



Resident patent applications per USD 100 billion GDP

Note: GDP data are in 2021 US purchasing power parity (PPP) dollars. The top 10 origins were included if they had a GDP greater than USD 25 billion PPP and more than 100 resident patent applications. Sources: WIPO Statistics Database and World Bank, August 2024.

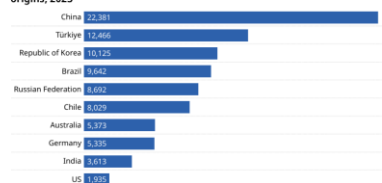
7. Resident patent applications relative to GDP for the top 10 origins, 2024



Resident patent applications per USD 100 billion GDP

Notes: GDP data are in 2021 US purchasing power parity (PPP) dollars. The top 10 origins were included if they had a GDP greater than USD 25 billion PPP and more than 100 resident patent applications. Netherlands refers to the Kingdom of the Netherlands. Sources: WIPO Statistics Database and World Bank, September 2025.

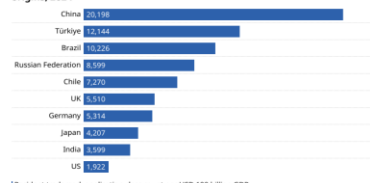
14. Resident trademark application class count relative to GDP for selected origins, 2023



Resident trademark application class count per USD 100 billion

Notes: GDP data are in 2021 US purchasing power parity (PPP) dollars. The 10 selected origins were included on the basis of having a GDP greater than USD 575 billion PPP and a resident trademark application class count of at least 46,000. Sources: WIPO Statistics Database and World Bank, August 2024.

14. Resident trademark application class count relative to GDP for selected origins, 2024

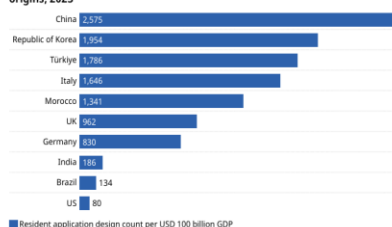


Resident trademark application class count per USD 100 billion GDP

Notes: UK refers to the United Kingdom. GDP data are in 2021 US purchasing power parity (PPP) dollars. The 10 selected origins were included on the basis of having a GDP greater than USD 595 billion PPP and a resident trademark application class count of at least 43,000. Sources: WIPO Statistics Database and World Bank, September 2025.

In the field of industrial designs, filing intensity is likewise concentrated in a limited number of economies. According to 2024 data, China (2,391) demonstrates the highest level of design filings relative to GDP, followed by Italy (1,636), Morocco (1,555) and Türkiye (1,387). At the same time, in several large economies such as the United States, this indicator remains relatively low (81 applications per USD 100 billion of GDP), which may reflect differences in industrial structure and national strategies for design protection:

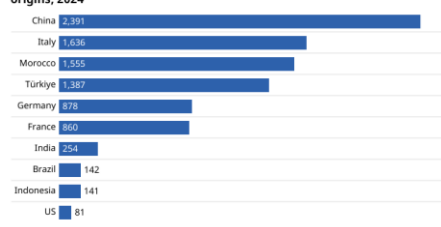
19. Resident application design count relative to GDP for selected origins, 2023



Resident application design count per USD 100 billion GDP

Notes: GDP data are in constant 2021 US PPP dollars. Origins were selected based on the top origins list in terms of application design count and GDP data availability. n.a. indicates not available. Sources: WIPO Statistics Database and World Bank, August 2024.

19. Resident application design count relative to GDP for selected origins, 2024



Resident trademark application class count per USD 100 billion GDP

Notes: GDP data are in constant 2021 US PPP dollars. Origins were selected based on the top origins list in terms of application design count and GDP data availability. Sources: WIPO Statistics Database and World Bank, September 2025.

Indicators of filing intensity adjusted for economic size provide valuable insights into the effectiveness of national innovation and intellectual property policies [8]. High values often reflect a combination of strong R&D investment, supportive innovation policies, tax incentives for innovative firms, and well-developed institutional infrastructures for intellectual property protection.

5. Conclusion

The analysis of the latest statistical data published by the World Intellectual Property Organization allows several key conclusions to be drawn regarding the development of the global intellectual property system in 2023–2024. First, the overall level of intellectual property activity remains consistently high across the main categories of industrial property rights. Patent, industrial design and utility model filings continue to demonstrate moderate growth, while trademark activity remains relatively stable despite short-term fluctuations. This confirms the continuing importance of intellectual property as a strategic asset in the modern knowledge-based economy. Second, the geographical distribution of filing activity demonstrates an increasingly pronounced regional concentration in Asia. Countries such as China, the Republic of Korea and Japan maintain leading positions in the global intellectual property system. At the same time, the growing share of China in global patent filings and the strong presence of Asian offices across multiple IP categories indicate a structural shift in the global innovation landscape. Third, the analysis highlights the growing role of emerging and middle-income economies in the global intellectual property system. Countries such as India, Brazil, Indonesia, Thailand and Ukraine demonstrate increasing filing activity, particularly in patents, utility models and industrial designs. This trend reflects the gradual expansion of innovation ecosystems beyond traditional technological centers. Taken together, these developments suggest that the global intellectual property system is undergoing both quantitative expansion and structural transformation. While the overall number of filings continues to grow, the geography of innovation is becoming more diversified, with new regional actors strengthening their positions in the global innovation landscape. These trends create new challenges for the international governance of intellectual property, including the need for greater coordination of national IP policies, the adaptation of regulatory frameworks to rapidly evolving technological sectors, and the integration of intellectual property statistics into broader economic and innovation policy analysis. In this context, intellectual property statistics are becoming an increasingly important analytical tool for understanding global innovation dynamics and shaping evidence-based economic and technological policies.

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A Review on Various Deep Learning Techniques for the Detection of Brain Disorders

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Abstract. Electroencephalography (EEG) is a method that has established itself for the diagnosis of brain-related and mental disorders along with its ability to provide high temporal resolution. This review presents the EEG-based diagnosis of brain disorders, knowledge, and understanding. The research covered the disorders of epilepsy, Alzheimer's disease, ADHD, sleep disorders, schizophrenia, depression, and Parkinson type. These studies were collected from 25 peer-reviewed papers about the use of the following techs: convolutional neural networks (CNNs), long short-term memory networks (LSTMs), transformers, graph convolutional networks (GCNs), spiking neural networks (SNNs), and explainable AI (XAD). Reported accuracies varied from 83% in pediatric sleep staging up to over 98% in seizure detection and Alzheimer's disease classification. Results highlight the growing use of hybrid DL configurations, patient-specific modeling, and interpretable systems - the latter being key to real-time clinical usage of EEG analysis. The range of future studies might encompass privacy-preserving federated learning, multimodal fusion with neuroimaging and biomarkers, and disease progression predictive modeling. This review delineates recent advancement as well as a blueprint for the AI-driven EEG translation to clinical practice.

Keywords. Electroencephalography (EEG), deep learning (DL), seizure detection, neurological disorder diagnosis, explainable artificial intelligence (XAI).

1. Introduction

Electroencephalography (EEG) is among the most popular non-invasive neuroimaging modalities for evaluating brain function and recognizing neural abnormalities. It provides excellent temporal resolution, is relatively cheap and portable, hence being a vital tool for both the clinic and research.

Conventionally, the interpretation of EEG has been dependent solely on the experts' visual checking, which is naturally subjective, time-demanding, and limited to very faint pattern recognizing. The adoption of computational methods that could facilitate in rendering correct, efficient, and objective EEG signal interpretations to the clinicians has been drawn by these limitations.

Indeed, over the last few years, a lot of promise has been shown by the developments in the field of artificial intelligence (AI) and deep learning (DL) for an automated EEG-data analysis. Herein lies a fundamental difference between traditional machine learning and the latter: whereas the former is feature-driven, with most of the features engineered by hand, the latter is feature extraction-driven, where complex hierarchical features can be automatically extracted from raw or minimally processed EEG signals by deep learning architectures such as convolutional neural networks (CNNs), recurrent neural networks (RNNs), long short-term memory networks (LSTMs), and transformers [1–4].

These are just some of the indisputable instances where deep learning methods have been put to work in a very broad spectrum of brain disorders, epileptic syndromes, Alzheimer's disease, attention deficit hyperactivity disorder (ADHD), sleep disorders, schizophrenia, depression, and Parkinson's disease among others [5–10]. The reported performances scope is task and dataset dependent, for example, lightweight pediatric sleep staging systems designed for interpretability and clinical feasibility reach approximately 83% accuracy [16], while seizure detection and Alzheimer's classification models attaining over 99% accuracy [2,6] have been reported.

The recent research has demonstrated the deployment of different and varied methods ranging from hybrid architectures combining CNN and LSTM [6, 19], to sophisticated attention-based frameworks such as transformers [1,3,4,17]. The latter is noted for high interpretability, which is very valuable in attaining clinical trust. The utilization of the explainable artificial intelligence (XAI) methods, such as LIME and SHAP, is just another example which reflects the place of interpretability not only in scientific discourse but more importantly in the clinical trust [5, 25]. Multimodal fusion, one where EEG can be combined with other bio signals or sensors to achieve a more robust diagnosis, is another potential area that is gaining traction [23].

Despite these advancements, there still exist some problems such as small sizes of datasets, class imbalance, poor generalization across patient populations, and the lack of longitudinal studies that capture disease progression.

The current review is an attempt to amalgamate the data related to the diagnosis of brain disorders based on EEG published between 2020 and 2025 while using deep learning methods. The review investigates 25 peer-reviewed research papers ranging over epilepsy, Alzheimer's disease, ADHD and other cognitive disorders, sleep disorders, schizophrenia, depression and Parkinson's disease. It not only helps in the comprehension of EEG-based deep learning for brain disorder diagnosis by the academic community and clinicians but at the same time also points out the areas of research that require more studies and the future directions those studies may take by summarizing recent trends, showcasing methodological breakthroughs, and pinpointing research gaps in the field.

2. Definition of Concepts

2.1 Electroencephalography (EEG)

Electroencephalography (EEG) is a non, invasive method that records the brain's electrical signals via electrodes that are attached to the scalp. The main characteristics of EEG are high temporal resolution, low cost, and the potential of capturing both transient and long, term brain dynamics. The application of EEG signals is very broad in the medical diagnostics field of the diseases of the nervous system and the mind, which are the case of epilepsy, Alzheimer and sleep disorders among others. However, raw EEGs are typically noisy, high dimensional and non-stationary, which leads to the difficulty of experts in decoding them and thus computationally assisted methods have been implemented as a solution to this problem [1, 7].

2.2. Artificial Intelligence and Deep Learning

Artificial intelligence (AI) is a term used for the capability of a computer or a computer, controlled robot to do tasks that are usually done by humans, which include decision making, pattern recognition, and so on. Deep learning (DL) models have gained a lot of traction in the field of EEG analysis and have become the leading ones within the total AI framework. One of these models is the convolutional neural networks (CNNs) which is efficient in drawing the

spatial patterns while the other is the recurrent neural networks (RNNs) and long short, term memory networks (LSTMs) which are designed to extract the temporal dynamics [6, 19]. Lately, attention, based paradigms like transformers have been integrated for far, reaching sequence modeling in EEG [1, 4, 17] and brain connectivity studies have propelled the use of graph convolutional networks (GCNs) [8, 13]. The diversity of methods has been further broadened by the inclusion of spiking neural networks (SNNs) and explainable AI (XAI) frameworks [14, 25].

2.3 Clinical Disorders in Focus

The first question asks for the clinical conditions that appear in this review and represent areas of research based on the diagnostic use of EEG.

- **Epilepsy:** It is a disease where abnormal neuron discharges are the cause of repeated seizures besides that EEG is used as a gold standard in seizure detection and prediction [2, 3, 5].
- **Alzheimer's Disease:** A neurodegenerative disorder characterized with gradual decline in cognitive abilities. EEG changes like slowing rhythms and interrupted connectivity can act as biomarkers [6, 9].
- **Attention Deficit Hyperactivity Disorder (ADHD):** It is a neurodevelopmental disorder whose main symptoms are inattention and hyperactivity. Some EEG abnormalities that have been found include changed spectral power and disrupted connectivity [11, 15].
- **Sleep Disorders:** The above, mentioned diseases are studied by polysomnography (PSG), which main stages of the sleep are carried out by EEG [16, 18].
- **Schizophrenia and Depression:** Mental diseases that differ from each other only by the presence of some subtle but detectable EEG biomarkers that are the changes of oscillatory patterns and connectivity [19, 21].
- **Parkinson's Disease:** It is a disorder of the central nervous system that affects movement, the symptoms can be very helpful EEG features will be clearer when you combine the detected features with the help of wearable sensor data [22, 23].

Once these key concepts have been identified, the stages for an organized review of the present research trends, methodologies and results across these disorders are established.

3. Current Research Trends

3.1 Epilepsy and Seizure Detection

Just with the advent of attention, based models, epileptic seizure prediction has made substantial headway. Reporting accuracies over 95% for transformer designs applied to benchmark scalp EEG datasets, Yan et al. [1] and Bhattacharyya et al. [2], both achieved striking performance comparable to or better than conventional recurrent models. Zhu et al. [3] elevated that level further by blending multidimensional transformers with the recurrent neural network, which allowed him to exceed 96% of accuracy. By coupling raw time series data together with spectrogram features using a dual, modality transformer, Qin et al. [4] not only increased the accuracy to more than 97% but also gained more robustness for cross, patient experiments. Reaching roughly 94% of accuracy while also promoting interpretability, Ahmad et al. [5] fused efficient feature selection with an explainable classifier. Basically, these results collectively depict the striving for highly accurate (>94%) seizure detection pipelines

of which transformers and hybrid methods dominate the field by setting the bar for new benchmarks.

3.2 Alzheimer's Disease

Among the various disorders in the review, EEG, based Alzheimer's classification retains some of the highest accuracies. DeepADNet (CNN, LSTM) proposed by Ho et al. [6] attained over 98% accuracy across different stages of the disease. AlSharabi et al. [7] leveraged empirical mode decomposition combined with deep learning and achieved approximately 95% accuracy in clinical cohorts. Shan et al. [8] utilized a spatial, temporal GCN on EEG, derived connectivity, and the accuracy ranged from 92% to 96%, while Cao et al. [9] supported with a deep pyramid CNN showed a performance of over 97%. Kachare et al. [10] presented a lightweight CNN (LCADNet) that could efficiently maintain the balance with the accuracy close to 94%. These results indicate that EEG classification of Alzheimer's is highly feasible if most of the approaches are capable of more than 90% accuracy.

3.3 ADHD and Cognitive Disorders

The detection of ADHD has been gradually progressing, but it still generally lags the results of the seizure and Alzheimer's research fields. Altun et al. [11] created CNNs with scalograms and reported the accuracy in the range of 85, 88%. Nonlinear features and wavelet transforms were used by Joy et al. [12], and they were able to achieve about 87% of the accuracy. Li et al. [13] made a step forward toward graph convolutional networks and claimed 90% of accuracy with multi, domain features. Baibulova et al. [14] stressed that one could keep the classification accuracy at the level near 89% while focusing on interpretability. Alhussen et al. [15] utilized NeuroDCT, ICA with AttentionNet optimization and attained the accuracy of more than 91% at the early stage of ADHD detection. The overall scope of accuracies for studies related to ADHD is from 80% to 92%. Deep learning, although offering substantial improvements, shows that more significant gains might be possible only with larger datasets and multimodal inputs.

3.4 Sleep Disorder

EEG remains the principal method of research in sleep staging and the operational range largely depends on the variety of models. Zhu et al. [16] built a lightweight edge AI model for sleep staging in children using single, channel EEG and the accuracy obtained was 83%. This was in support of their goal to enable deployment in low, resource environments. Fox et al. [17] demonstrated that a full, night polysomnography, trained transformer got better results (~91% accuracy) as it could capture the long, range sleep dynamics. The best results of the market were obtained by Lee et al. [18] with an explainable vision transformer on multimodal PSG at the level of over 92%. Besides providing clinically relevant visual explanations, this development clearly shows the trade, off that exists between lightweight edge systems and high, performing but computationally heavier transformer, based architectures.

3.5 Schizophrenia and Depression

The EEG biomarkers of psychiatric disorders are less obvious thus; the accuracies are modest but still encouraging. The CNN, LSTM models reported by Shoeibi et al. [19] were able to achieve an accuracy of around 87% for schizophrenia diagnosis. The attention, based EDT model created by Ying et al. [20] for depression got the accuracy in the range of 88, 90%.

The application of multichannel CNN to schizophrenia EEG resulted in ~85% of accuracy for the differentiation of patients from the control group [21]. Although these numbers are lower than those for seizure or Alzheimer’s detection, they nonetheless confirm the promise of deep learning in psychiatric domains where diagnostic hints are few and faint.

3.6 Parkinson’s Disease and Multi, Disorder Diagnosis

With multimodal data, the Parkinson’s disease studies are a different story. Li et al. [22] applied a CNN, GNN hybrid to EEG, and the outcome was the approximate 91% of accuracy. Zhang et al. [23] enrolled EEG together with data from wearable sensors and thus, substantially, the performance made a big jump and was over 93%. In brief, the findings suggest that brain activity alone may not fully depict Parkinson’s illness however, combining different modalities can aid in the accuracy of the diagnosis.

Table 1. Comparative Summary of Reviewed Studies

Disorder	Dataset (if reported)	Methodology / Model	Reported Accuracy / Findings	Ref.
Epilepsy/ Seizures	CHB-MIT, scalp EEG (various)	Transformer models [1,2]; Transformer + RNN fusion [3]; Dual-modality transformer [4]; Feature selection + explainable classifier [5]	>95% (up to ~97% in hybrid/dual- modality models)	[1–5]
Disorder	Dataset (if reported)	Methodology / Model	Reported Accuracy / Findings	Ref.
Alzheimer’s Disease	Resting-state EEG (clinical)	CNN-LSTM hybrid (DeepADNet) [6]; EMD + DL [7]; Spatial–temporal GCN [8]; Deep Pyramid CNN [9]; Lightweight CNN (LCADNet) [10]	90–99% (DeepADNet and pyramid CNN >97%)	[6–10]
ADHD & Cognitive Disorders	Clinical ADHD EEG datasets	Scalogram + CNN [11]; Non- linear + wavelet [12]; GCN multi-domain [13]; Interpretable hybrid DL [14]; AttentionNet with NeuroDCT- ICA [15]	80–92% (best ~91% with AttentionNet optimization)	[11–15]

Sleep Disorders	Paediatric and adult PSG datasets	Lightweight edge AI [16]; Full-night transformer [17]; Explainable vision transformer on multimodal PSG [18]	83% (lightweight paediatric) to >92% transformer-based)	[16–18]
Schizophrenia & Depression	Multichannel EEG (clinical)	CNN-LSTM [19]; Attention-based EDT [20]; CNN for schizophrenia [21]	~85–90% across disorders	[19–21]
Parkinson's Disease	EEG + wearable sensor fusion	CNN-GNN hybrid [22]; EEG + wearable fusion model [23]	~91% (EEG-only) to >93% (EEG + wearable fusion)	[22–23]
Methodology / General	—	Systematic review [24]; XAI with LIME/SHAP for seizure detection [25]	~94% accuracy with explainability integration. Highlighted data scarcity, interpretability, need for trust	[24–25]

4. Models and Methodologies in EEG-Based Diagnosis

4.1 Convolutional Architectures

Convolutional neural networks (CNNs) are still the major components of EEG, based classification, especially for Alzheimer's disease and movement disorders. The development of CNNs has brought about commendable results, with Alzheimer's disease diagnosis often scoring between 90% and 99% accuracy [6, 9, 10]. Pyramid CNNs [9] got around 97% while light CNNs like LCADNet [10] kept the good performance with about 94% accuracy. Besides, CNNs applied to schizophrenia [21] and Parkinson's disease [22] have also made a breakthrough where the performance accuracies ranged 85, 91%. These performances point to CNNs as dependable spatial feature extractors yet, their capacity may reach a ceiling without mixing with other models.

4.2 Recurrent and Sequential Models

Recurrent models long short-term memory networks (LSTMs), are good at representing the time, varying dependencies of EEG signals. CNN, LSTM combinations like DeepADNet used for Alzheimer's [6] and schizophrenia [19] classification have been found to be consistently accurate in the range of ~87, 98%, thus they surpassed single, model baselines. Their effectiveness is due to the coupling of CNN spatial features with LSTM's capability of following sequential EEG variations. On the other hand, RNN, based architectures may be

slow when it comes to running heavy computations and they might not be as scalable as transformer architectures.

4.3 Attention Based Transformers

The reason why transformers have quickly evolved seizure detection, ADHD diagnosis, and sleep staging is that they can handle long dependencies efficiently. High accuracies above 95% have been the norm in seizure prediction literature [1, 4], with one of the best performances of 97% achieved by a dual, modality transformer [4]. Attention, based models for ADHD scored >91% [15] and transformer, based sleep staging stayed over 90% [17, 18]. These results indicate that transformers are setting new levels of performance across different disorders, although their high computational cost still makes it tricky for real, time clinical use.

4.4 Graph Based Models

Graph neural networks (GNNs) and graph convolutional networks (GCNs) use the brain's connectivity patterns to enhance classification. Shan et al. [8] achieved 92, 96% in Alzheimer's detection by implementing a spatial, temporal GCN, and Li et al. [13] reported 90% in ADHD detection by utilizing multi, domain graph features. Also, CNN, GNN hybrids have helped Parkinson's diagnosis with the accuracy reaching up to 91% [22]. These results show network level biomarkers can be highly relevant to clinics, particularly in diseases related to disrupted connectivity.

4.5 Time, Frequency and Feature Engineering Approaches

Feature extraction is still needed when deep learning alone is not enough. The use of scalograms with CNNs for ADHD detection led to an accuracy of about 85, 88% [11] while nonlinear + wavelet features reached 87% [12]. Empirical mode decomposition (EMD) combined with deep models was given an accuracy of about 95% for Alzheimer's [7]. The development of feature, engineered approaches might lag the state-of-the-art deep models, but they are still significant for the sake of dataset size and model interpretability.

4.6 Explainable AI (XAI)

Interpretability is a key aspect of clinical trust. For example, Ahmad et al. [5] obtained nearly 94% accuracy in seizure detection while maintaining feature, level explanations. In sleep staging, vision transformers [18] gave over 92% accuracy together with saliency maps for assisting clinical validation. In their work, Khan et al. [25] added LIME and SHAP to seizure detection pipelines, thus the system was able to get about 94% of accuracy with interpretable predictions. These studies collectively provide evidence that explainability could be implemented with little accuracy tradeoff, thereby increasing confidence in AI based diagnosis.

4.7 Multimodal and Edge Friendly Systems

Efficiency and practicality are other advantages that are coming more into the limelight. For instance, Zhu et al. [16] created a child sleep staging system with roughly 83% accuracy made possible using single, channel EEG and edge AI, proving its great potential in places with limited resources. Moreover, the combination of EEG and wearable sensors led to a rise in the detection of Parkinson's disease to over 93% [23] which was higher than that of EEG only studies. The importance of such strategies lies in the equilibrium between model complexity, computational efficiency, and clinical deployability.

5. Discussion and Challenges

The reviewed studies collectively demonstrate the rapid evolution of EEG, based deep learning for brain disorder diagnosis. Various key points come up when studying the methodologies, the results, and the clinical use cases.

5.1 Performance Across Disorders

The most researched diseases based on the EEG method are still epilepsy and Alzheimer's disease, for which several transformers, based and hybrid CNN, LSTM models have reported the best part of their accuracy above 95% [2, 4, 6, 9]. On the other hand, the study of ADHD, schizophrenia, and depression has made less progress and the accuracy is usually between 80 and 90 % [12, 14, 20]. The difference between these two groups is connected both to the subtlety of EEG biomarkers in psychiatric conditions and to the smaller sizes of the available datasets. The focus of sleep staging models is, above all, on computational efficiency, especially in the case of pediatric populations, so sometimes the accuracy is sacrificed for deployability [16]. The studies on Parkinson's disease have become increasingly inclined towards multimodal fusion to make up for the limited diagnostic power of EEG alone [22, 23].

5.2 Methodological Trends

Many methodological changes come to light in the review summarized in the paper. Firstly, attention, based models and especially transformers are gaining ground very rapidly and this is the reason why we find them in the forefront of the seizure prediction and the sleep analysis fields. The main property that is highlighted is their capability to handle very long sequences of data, which is a very common case in EEG data processing [1, 3, 17]. Secondly, the use of the graph, based method is becoming more prominent, for example in brain connectivity and alterations of connectivity in Alzheimer's disease and ADHD [8, 13]. Third, putting the interpretability into the spotlight is an imperative issue, not an option anymore; hence, the use of AI models with explainability features that are not a retrofit but are really integrated in the design of the model, like in the case of attention, based annotation with SHAP/LIME [5, 25] and vision transformers for sleep staging [18].

5.3 Data and Generalization Issues

Most of the studies still rely on small or, at best, medium, size datasets collected from a single site, although a lot of methodological advances have been achieved. This is the main reason that their generalizability is very limited. Without tuning the model performance to each specific patient, the accuracy reported is generally not as high. However, doing that reduces the applicability of these models to new populations. Not many studies have done a cross, dataset validation, which is a crucial step for the clinical use of models. Furthermore, the problem of class imbalance still exists and is more noticeable in, for instance, multi, class Alzheimer's disease classification [6, 10] as well as seizure prediction tasks, wherein the number of preictal events is small, thus leading to data sparsity [1, 4].

5.4 Computational and Practical Constraints

The various transformer could indeed be at the forefront of the highest, performing models yielding excellent accuracy; however, their heavy computational complexity is one of the stumbling blocks for the deployment of the models in clinical environments where resources are limited. Users of LCADNet [10] and edge, supported sleep staging models [16]

that are lightweight in terms of architecture may somehow bridge this space, yet several compromises should be accepted in terms of predictive capabilities. Efforts to strike a balance between performance and efficiency are still ongoing and this is particularly the case for real, time applications which represent a serious challenge.

5.5 Clinical Translation and Trust

For the clinical implementation to become a reality apart from accuracy, the factors of interpretability, robustness, and smooth integration into the existing workflows, etc. are very important. Even though the use of explainable AI methods [5, 18, 25] makes a step toward visibility, still, these outputs should be reconfirmed for being accurate reflection. Plus, the ethical concerns like the privacy of patient data in Internet of Medical Things (IoMT) scenarios, to name one, are still undeveloped. Few studies have taken account of evolutions in federated learning or privacy, preserving AI research.

6. Conclusion

This review involved 25 peers, reviewed studies published between 2020 and 2025 that had deep learning as the focus for EEG, based brain disorder diagnosis. The summary of the data shows that epilepsy along with Alzheimer's disease are the most studied disorders to date, while several transformer, based as well as hybrid CNN, LSTM models have also reported their accuracies to be above 95%. On the other hand, research related to psychiatric conditions, for instance, ADHD, schizophrenia, and depression, is still at a very initial stage with low diagnostic performance that can be explained by both the complexity of their biomarkers and the limited availability of large datasets. Sleep disorder studies focus on lightweight and edge, friendly models. At the same time, Parkinson's disease research is progressively depending on multimodal fusion with wearable sensors.

From a methodological perspective, the field is undergoing a transition embracing three major directions: (i) attention, based architectures that capture long, range temporal dependencies, (ii) graph, based models that exploit connectivity information, and (iii) explainable AI frameworks that provide transparency for clinical users. However, despite these improvements, challenges and difficulties remain in terms of the diversity of datasets, class imbalance, generalizability of models, and the need for computationally efficient solutions. The process of moving into clinical practice also entails the necessity of more robustness, privacy, preserving collaboration, and validation of the interpretability methods.

In the future, researchers should focus on using federated learning as the priority which is the technique that facilitates multi, site data sharing without compromising patient privacy, followed by multimodal integration of EEG with imaging and physiological sensors, and finally longitudinal modeling of disease progression. These steps would not only speed up the deployment of AI, driven EEG analysis in real, world clinical settings but also, eventually, they would elevate diagnostic accuracy, foster clinical decision, making and contribute to patient health and well-being.

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Machine Learning and Deep Learning for Cuff-less Blood Pressure Monitoring: A Review of Advances and Future Directions

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Abstract. Blood pressure is known to be the leading cause of cardiovascular disease. However, devices based on cuffs only provide measurements from time to time and what is more, these readings are often inaccurate. A new development in IT technology, that is ML and DL, has already allowed the creating of the continuous, cuff-less, and non-invasive monitoring systems. Several ML methods, including Random Forest, Gradient Boosting, and SVR have been successfully used for physiological signals (ECG, PPG, and ABP) to meet global standards. One large-scale Random Forest study (~30 million beats) is a perfect example in which the performance was very strong when a subject-personalized model was used. Some deep learning architectures, e.g. CNNs, LSTMs, BiLSTMs, and hybrid CNN–LSTMs, are capable of automatic feature extraction from various types of signals, and even from video-based rPPG, through certain means like clustering-based preprocessing, PBS fusion, and Conv-LSTM have succeeded in reaching the accuracy level required for clinical application, and in fact, they are also rated as Grade A by BHS. Such advancements are very attractive in the context of wearable, real-time monitoring that can detect the occurrence of nocturnal hypertension, among other hidden risks, an example being a device based on these novel technologies. But along with benefits come certain issues, such as motion artifacts, population-wide generalizability, and calibration-free accuracy, which are picked up as sources of problems needing multimodal sensor fusion and personalized hybrid models to become clinically adopted solutions.

Keywords. Blood, Pressure, Monitoring, Cuff-less, Measurement, Machine Learning (ML), Deep Learning (DL), Physiological Signals (ECG), PPG, ABP, rPPG), Wearable Devices, Multimodal Sensor Fusion

1. Introduction

Blood pressure (BP) is probably one of the most instrumental physiological measurements that depicts the status of the cardiovascular system. It is essential to regularly check BP to be able to detect and control such disorders as hypertension, diabetes, and heart failures. Usually, blood pressure measurement is performed by such methods as auscultatory and oscillometric which rely on an inflatable cuff.

In general, these methods are accurate, but they are also inconvenient, only allow intermittent measurements, and cannot be used for real-time monitoring. On the other hand, continuous blood pressure monitoring provides a way for the earliest detection of hemodynamic changes, thus improving patient outcomes and allowing preventive care.

Wearable sensors and computational intelligence that are the areas of recent advances have been instrumental in changing the paradigm of cuff-less BP monitoring that is now possible with biosignals such as photoplethysmography (PPG), electrocardiography (ECG),

and arterial blood pressure (ABP) waveforms. In particular, PPG has turned into a strong signal because of its ease of use, ability to be carried anywhere, and being inexpensive. Nevertheless, the nonlinear relationship between PPG and BP is difficult and affected by several base and surrounding factors. The problem has led to the implementation of Machine Learning (ML) and Deep Learning (DL) methods to create a model for the complex mapping that links the PPG signal features with the BP values.

Need for Intelligent BP Estimation

ML and DL models can identify that complexity in the interrelations and nonlinearities in biosignals, which, by traditional regression-based models, cannot be accounted for. In addition, they can learn from extensive datasets and apply what they have learned to new situations, which makes them perfect for personalized and continuous BP monitoring.

The deployment of these models together with wearable gadgets, edge computing, and remote monitoring systems is a great innovation in the field of digital health and telemedicine bringing the promise of cuff-less BP estimation being highly accurate and feasible in real-life situations.

2. Definition of Core Concepts

2.1 Photoplethysmography (PPG)

In principle, photoplethysmography evaluates transmitted light through the small blood vessels near the skin's surface, so it is considered a cuffless approach for blood pressure estimation. A little LED sends light into your skin. The amount of light reflected or transmitted through the tissue is detected by a photodetector which notes changes in brightness. Essentially, that rhythmic volume variation of each heartbeat picked up through the photoplethysmogram tells you how blood flows through your circulatory system.

Features Derived from PPG:

Measurements taken over time - like how long a pulse takes to travel, its duration, alongside heartbeats per minute - fall into the category of time-domain features. Looking at how signals change - their energy across different frequencies, likewise their patterns using wavelets - gives us key characteristics.

A pulse's shape reveals itself through its high points - when the heart squeezes, then relaxes - a small dip between them, likewise the total space beneath the waveform. You can gauge characteristics using three measurements: how rigid something is (Stiffness Index), how well it bounces back (Reflection Index), alongside a comparison of pulse strength (Pulse Intensity Ratio).

Advantages: Tiny, they slip right in without fuss - also, they don't break the bank. Ideal for devices you wear or that track from a distance. These tools work well alongside machine learning - even advanced deep learning - allowing for ongoing, automatic blood pressure tracking. **Challenges:** Movement blurs the images, likewise does ambient brightness. How a signal behaves can shift due to age, warmth, likewise complexion.

2.2 Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL)

Computers showing human-like smarts - reasoning, seeing things, choosing what to do - fall under Artificial Intelligence. Within this field, machine learning likewise deep learning play key roles in figuring out blood pressure. Machine Learning (ML) Algorithms learn from data - they spot what usually happens through careful calculations. Models that predict based on relationships include straightforward linear methods, also more complex random forest approaches, likewise gradient boosting techniques. Grouping tools - specifically K-Means - assist when data spreads out or characteristics shift. Sometimes, Support Vector Machines

really shine when data isn't a straight line – instead of simple connections, they handle curves beautifully.

Deep Learning (DL) utilizes multiple layers so it can independently discover what's important within data. CNNs work by pinpointing where things happen within a pulse signal. They're built to grab those specific details. Heartbeats unfold over time, a pattern RNNs alongside LSTMs help us decipher. They reveal how each beat connects to what came before.

A BiLSTM learns patterns by looking at sequences forwards then backwards - essentially considering context from every angle. Consequently, it grasps time-based details more thoroughly. These designs blend convolutional neural networks - good at spotting patterns – with long short-term memory networks that excel at understanding sequences. Essentially, one part finds what's important, while the other figures out how things change over time. Focusing on key parts of pulse signals - rather than everything at once - helps forecasts become more reliable.

2.3 Clinical Disorders in Focus

1). Hypertension (High Blood Pressure):-Heart disorder - a major health problem - often leads to fatal consequences such as heart attacks or strokes. Traditional blood pressure measuring devices are not always able to detect blood pressure that spiked or dropped briefly, especially during sleep. Smart computer systems that integrate two different types of deep learning can compute blood pressure with an error of less than five millimeters of mercury, thus enabling them to be used in everyday situations. By doing so, it locates the hidden high blood pressure that is not visible to doctors and thus allows the creation of personalized medicine treatment plans just for you.

2). Hypotension:-If blood pressure is lowered suddenly, the patient may experience dizziness, fainting, or in the most extreme cases, may suffer a collapse that could even lead to his death, i.e., particularly, it may happen after a surgical operation or while the patient is in a critical condition. Monitoring should be done all the time, and if this is not the case, there is a risk that organs will be damaged. Advanced technologies recognize very small changes in the monitored parameters to be able to predict blood pressure decreases.

3). Diabetes Mellitus:-One of the scenarios is the hardening of the arteries which are also involved in the malfunction of the body's homeostasis. How well the heart and blood vessels are functioning can be indirectly judged by putting emphasis on blood pressure monitoring. Doctor's attention is now drawn to artery health by using pulse signals through which we reveal important parts - for instance, how light reflection changes with pulse transit time.

4). Atherosclerosis and Peripheral Artery Disease (PAD):-The condition whereby the arterial walls become less pliable due to the accumulation of fatty substances - a journey thus intermixed with the perils of stroke or cardiac events - eventually takes place at the arteries. Early issue comes to light through the method of assessing how the arteries' flexibility has changed. The research team has shown that machine vision systems can detect the altering of the vessels' structures - it can be changes due to aging or/and arteriosclerosis.

5). Sleep Apnea and Circadian BP Disorders:-Sleep apnea - the cessation of breath during sleeping - is followed by an increase in blood pressure which can be deemed the main cause of heart inflection. Overnight detection of hypertension can be instrumental in uncovering incidences of non-dipping during sleep. During sleeping hours, smart gadgets not only monitor but also infer the changes in blood pressures resulted from sleep apnea by means of photoplethysmography.

6). Chronic Kidney Disease (CKD):-Hypertension may often be observed in parallel with the shortcoming of kidneys, however, it is not only that, but high blood pressure is the main culprit that causes kidney problems to co-morbid cases get escalated additionally. It is through the thorough observation of BP that the medics find they can adjust the dosage of medicines correctly. Patients suffering from hypertension and having trouble with kidneys are given a chance for home follow-up via AI without wristbands which is a great convenience in the absence of those cuffs.

7). Cardiovascular Disease and Stroke Risk:-Blood pressure volatility, to a large extent, may be the harbinger of heart diseases ahead. Time-tracking models that are built similar to brain functions – memory of past events, prediction of coming ones – are able to locate changes in blood pressure which are rare and thus, signal a potential danger. People who are in the most severe condition and have undergone operations must have their blood pressure checked all the time - every moment counts here.

3. Current Research Trends

3.1. Hypertension and Cardiovascular Disease

Focus of research: Keeping an eye on blood pressure without a cuff is still mostly focused on hypertension. Research – consider work by Xing and others in 2020 – alongside collections of data like PulseDB, highlights how valuable constant tracking can be for spotting ongoing or hidden high blood pressure. **PPG-based innovations:** Using several wavelengths alongside readings from multiple locations on the body boosts how well pulse wave analysis lines up with artery health - specifically, how stiff arteries are, also blood pressure when the heart beats. **Deep learning systems** - combining CNNs, LSTMs, moreover attention mechanisms - detect minor shifts in waveforms that signify alterations in blood vessel resistance.

Impact:-Keeping a close watch helps spot high blood pressure quickly, allows doctors to tweak treatments, moreover forecasts heart problems - like strokes or heart attacks. **Trend:**-Wearable devices - like smartwatches or fitness trackers - can now include blood pressure sensors, enabling people to monitor their hypertension at home while also letting healthcare providers keep a distance watch on things.

3.2. Diabetes Mellitus and Vascular Stiffness

Research direction: Diabetes changes blood vessel flexibility, impacting tiny blood flow - this shows up in pulse wave patterns. Researchers are now exploring measurements from these waves, like how stiff arteries are, to digitally track harm diabetes does to circulation. **AI application:** To figure out blood pressure also how well vessels stretch, machine learning tools - like LightGBM yet SVR - employ these characteristics. Models merge heart rate along with electrical signals from the heart so they can foresee blood pressure shifts linked to diabetes harming nerves.

Trend: Doctors are beginning to investigate whether tracking blood pressure without needles could help determine heart risks for people living with diabetes.

3.3. Sleep Apnea and Nocturnal Hypertension

Clinical problem: When breathing stops during sleep apnea, blood pressure jumps - but typical monitors often overlook those quick spikes. **Current research:** Nighttime pulse readings, examined by complex computer programs - specifically those remembering past patterns - reveal blood pressure changes linked to pauses in breathing. Devices that don't require a cuff track changes in heartbeat shape to gauge how serious sleep apnea is.

Trend: Wearable sensors detect your pulse, then smart software watches your sleep - together they give a full day's view of heart health alongside insights into how sleep relates to blood pressure.

3.4. Stress, Autonomic Disorders, and Mental Health

The sympathetic nervous system is activated during acute psychological stress, which can elevate blood pressure (BP) and alter the PPG pulse amplitude. Machine learning algorithms that use PPG combined with accelerometer data or skin conductance can identify BP spikes. DL systems trained on continuous PPG help measure stress patterns, autonomic regulation. Enables real-time stress identification or biofeedback for mental health interventions without intrusive monitoring.

3.5. Chronic Kidney Disease (CKD) and Organ Perfusion

Strict BP control is key to slowing disease progression. Non-intrusive PPG-based BP monitoring could allow for continuous hemodynamic status monitoring in the renal population during dialysis and at home.

In adaptive ML methods, BP estimation is patient-specific, by learning each patient's hemodynamic response to medication/fluids. Vascular compliance decreases with age, and as a result, PPG morphology features flattened systolic peaks. Age-aware models, such as the one designed by Xing et al. (2020), utilize age as a feature to improve blood pressure estimation. Transfer-learning methods tune models for elderly populations with corresponding vascular characteristics. Continuous and comfortable monitoring of BP benefits elderly patients and can be used in isolated systolic hypertension.

4. Comparative Summary of Reviewed Studies

Study	Dataset	Model/Approach	MAE (SBP/DBP)	Key Findings
Xing, et al., 2020	1086 subjects	Age-dependent MLR	~3–5 mmHg	Age-aware modeling improves BP estimation; calibration enhances accuracy
PulseDB (2021)	MIMIC- III, VitalDB	Benchmark Dataset	N/A	5.24M clean PPG segments; established standardized evaluation protocols
Multi-wavelength PPG (2022)	162 volunteers	ACNN–BiLSTM Fusion	1.67/1.15 mmHg	Multi- channel fusion achieved BHS Grade A
González et al., 2023	Sensors, UCI, BCG, PPG-BP	Benchmark for ML Models	<10 mmHg	LightGBM and SVR Were top- performing; established MASE for cross-dataset validation
Video-based rPPG (2024)	MIMIC-II	ResNet (Transfer Learning)	~2–3 mmHg	Achieved contactless BP estimation accuracy comparable to cuff-based methods

Models and Methodologies in PPG-Based Blood Pressure Monitoring

4.1 Overview

Figuring out blood pressure without a cuff uses smart tech alongside how our bodies work. It blends analyzing biological signals with computer brains for ongoing, precise health checks. Generally, this is what happens: Gathering bodily signals – perhaps pulse from light reflecting off skin, heart activity through electrodes, or even a video recording of those subtle shifts. Getting data ready - cleaning it, breaking it down, tossing out the bad parts.

Discovering what makes data special - whether by carefully designing signals or letting computers learn them on their own. Figuring out patterns, then guessing what happens next – using smart systems, maybe a mix of different kinds. Checking accuracy - fine-tuning tests for each person, fixing imbalances, meeting healthcare standards.

4.2 Signal Preprocessing and Representation Machine Learning Methods

Regression Models: To get forecasts based on what matters most, we employed both Gradient Boosted Regression alongside Random Forests - each a distinct way to pinpoint key influences. Grouping similar data beforehand helps results be more precise because it tames scattered information.

Deep Learning Methods

CNN-LSTM alongside BiLSTM models grasp how pulse shapes evolve over time, reflecting biological details. Focusing convolutional neural networks - ACNNs - sharpens what matters, discarding excess detail. Existing neural networks - think those initially built to recognize images - get a new job: figuring out blood pressure from pulse signals or videos. They aren't starting from scratch, instead they leverage prior knowledge.

Merge different signals - like heart rhythms alongside blood flow patterns - to build a more detailed picture.

4.3 Feature Engineering (Feat2Lab)

To understand your circulatory system, doctors look at several things - how long it takes a pulse to travel (Pulse Transit Time), the width of that pulse, how rigid arteries are (Stiffness Index), how waves bounce off artery walls (Reflection Index) alongside your heartbeat rate.

When facing tricky problems, algorithms like Random Forest, Gradient Boosting, yet also LightGBM often deliver strong results. A recent study by González and colleagues (2023) showed that - with limited data - LightGBM alongside Support Vector Regression worked better than more complex deep learning approaches.

It's easily understood, moreover performs well even when data is scarce.

4.4 Deep Learning Approaches (Sig2Lab and Sig2Sig)

Models - CNNs, tweaked ResNets, likewise CNN-LSTMs - forecast systolic/diastolic blood pressure straight from the pulse signal. Models called Sig2Sig rebuild complete blood pressure patterns utilizing either an encoder- decoder system or a U-Net design; this delivers more detailed insights for diagnosis. The attention CNN-BiLSTM system worked remarkably well - systolic blood pressure predictions were off by about 1.67 mmHg, diastolic by roughly 1.15 mmHg. These figures align with top benchmarks from the British Hypertension Society (as shown in a 2024 case study).

4.5 Personalization and Calibration

Models perform better when they consider age, gender, also body size - especially for people over fifty. This helps them work more reliably across different groups.

Calibration methods: Fine-tuning delivers greater accuracy, yet struggles when moved to new situations. Researchers are striving for blood pressure tracking without needing calibration – a real step toward hands-off health checks.

Wearable devices now tweak readings to better match your blood pressure - a small change making a big difference for personal health tracking.

4.6 Validation and Evaluation

To get trustworthy results, each subject's data was held back individually to test the system – a method known as Leave-One-Subject-Out or Hold-One-Set-Out – which keeps information from unintentionally influencing the evaluation (González et al., 2023).

We gauged performance using measures like average absolute error, root mean squared error, alongside how well values aligned - expressed as 'r'. To see if results stacked up against established medical guidelines, we checked against acceptable ranges for accuracy (within 5mmHg) also variability (under 8mmHg).

To fairly judge performance on different kinds of data, we employ the MASE measurement - it levels the playing field.

4.7 Emerging Deployment Trends

Now, tiny AI programs - like streamlined machine learning or small convolutional neural networks - run directly on devices such as watches and microchips, delivering instant results. Consequently, wearables possess onboard intelligence.

Cameras, using clever software built on existing designs, now gauge blood pressure without touching you – a boon for checkups at home or remotely through healthcare services.

Critical care just got a boost: new tech using PulseDB alongside VitalDB data performs as well as direct blood pressure readings - a big step forward for constant patient tracking.

5. Discussion and Challenges

5.1 Significant progress Feature-based Modeling

Researchers showed how to guess blood pressure (both top and bottom numbers) using a finger sensor. They used math tricks alongside things like pulse wave velocity, plus reflections within vessels, along with spectral entropy. The guesses got better when factoring in someone's age, stature, then mass; this was particularly true for older adults.

This new system, blending how sound waves behave alongside detailed characteristics, guesses blood pressure within **about 3 to 5 mmHg** - just as accurately as a typical arm cuff measurement. Researchers checked how well blood pressure estimates from pulse signals held up long term. They found accuracy waned because bodies change, likewise signals do.

5.2 Machine Learning Benchmarking

The research offered one way to judge machine learning methods for blood pressure readings, resolving disagreements about data handling alongside how results were measured.

Researchers tested eleven different methods - looking at how well they linked features to labels, signals to labels, also signals to other signals - using three setups: Feat2Lab, Sig2Lab, likewise Sig2Sig. Both LightGBM alongside SVR stood out using features, yet ResNet likewise U-Net performed best within deep learning approaches. MASE arrived as a way to judge how well things were going, making results easier to understand - even when comparing different datasets. What we learned by looking at things side-by-side. The research shows a give-and-take - easier understanding often means less effective results, likewise stronger outcomes frequently come at the cost of clarity. Simple models - those built on clear relationships between factors, like multiple linear regression - are easily understood.

Because they don't demand much computing power, these models work well in small, mobile health monitors. González and colleagues pointed out how flawed data handling - specifically, when training and testing use overlapping subjects - can artificially boost accuracy claims in blood pressure research. They emphasized rigorous, independent verification alongside consistent evaluation methods are vital for reliable results.

5.3 Data Quality and Diversity

Data is usually gathered carefully, yet frequently misses representation from various ages, backgrounds, or existing health issues. Interference alongside movement blurs the clarity needed for reliable results.

5.4 Calibration Drift

Xing and colleagues discovered personalized tuning boosts initial precision; however, its benefit fades quickly. Therefore, systems requiring ongoing adjustments - ones capable of learning as they go - are essential.

5.5 Generalizability and Overfitting

Trained systems frequently struggle with new groups because the data they learned from wasn't truly representative - people are different, after all.

5.6 Lack of Standardization

Before González and colleagues published their work, evaluating different algorithms wasn't straightforward - there simply weren't shared rules. Though things have improved, widespread use of standard tests alongside those results is still a challenge.

5.7 Regulatory and Clinical Validation

To be used anywhere, blood pressure tech relying on smart algorithms needs to meet global requirements - also prove its accuracy through thorough testing with patients first.

6. Conclusion

Non-invasive blood pressure tracking is changing thanks to a blend of smart devices, how we analyze signals, also machine learning. Initially, researchers like Xing showed adding biological insights - for instance, how arteries shift with age - improved estimates. More recently, González and others found deep learning systems, given enough good data, now rival traditional methods in precision. Getting rid of blood pressure cuffs for good - always on, always tracking - isn't simple. We still wrestle with reliable data, making sure systems work for everyone, then proving it all actually works in daily life. What comes next involves.

We're building AI that blends how bodies work alongside the power of advanced computing, creating systems both strong yet understandable.

Taking models already trained elsewhere, then adjusting them for new data. Tailoring performance to each user then letting it evolve ensures things stay dependable over time. To help research move forward honestly, we share data freely alongside clear testing standards.

Estimating blood pressure without cuffs holds real potential, yet turning this tech into something doctors can reliably use - something people actually want to use - requires collaboration between data experts, those who understand how the body works, and folks setting healthcare standards.

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Machine Learning and Deep Learning in Audiology: Pathways to Improved Diagnosis and Access

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Abstract. This paper is an exposition on the modalities of machine learning (ML) and deep learning (DL) application to audiology practice enhancement. Normal hearing assessment procedures still need personnel with special training and sophisticated instruments which pose a big barrier to accessibility. Ingenious smart systems can not only interpret audiograms but also detect the types of hearing loss and give speech understanding estimates with a great degree of accuracy. Apart from that, they also make the process of clinical diagnostic easier and thus, act as a support to the doctor in decision-making. Partnership with portable devices, health apps, and telemedicine platform for remote diagnosis remains a key driver of easier access to hearing care. Thus, the prospective study has to focus on bigger datasets, more interpretable models, and the stages of smooth transition from the clinical to the research environment.

Keywords. Hearing loss, audiometry, machine learning, deep learning, clinical decision support, telemedicine.

1. Introduction

Among the major sensory disorders, hearing impairment ranks high in the list of the most prevalent ones globally. It currently affects around 430 million people and is expected to affect 2.5 billion by the year 2050[2]. Pure-tone audiometry (PTA) is the gold standard of hearing assessment and is the main diagnostic tool that measures hearing sensitivity at different frequencies from 250 Hz to 8000 Hz through both air conduction and bone conduction [3, 14]. Nevertheless, traditional audiometry has considerable limitations owing to the barriers posed to it in that it heavily relies on specialists (audiologists, ENT doctors), and its equipment is usually quite costly (typically \$5,000-15,000 per unit) [3].

Moreover, the test takes a lot of time (15-20 minutes), and it is geographically inaccessible to the rural and resource-poor areas [15].

The lack of sufficient audiologists globally - which is estimated to be approximately 250,000 specialists needed to meet the current demand - causes great healthcare inequity. According to WHO data, more than 80% of people with hearing loss living in low- and middle-income countries remain undiagnosed and untreated, which causes a chain of effects including among others, cognitive decline, social isolation, and lower economic productivity [1, 15].

In the field of artificial intelligence, particularly in the areas of machine learning and deep learning, there are considerable breakthroughs, which were not available before, and which now open up possibilities to democratize hearing diagnostics [4, 5]. Automated audiogram interpretation systems can successfully imitate human expert performance and are free of bias, monotony, and error caused by different raters [4]. Besides, these systems can be

accessed through mobile applications, telemedicine services, and community health programs thus can be used on a large scale to reach the unserved population with the least infrastructural requirements [7, 10].

This research implements and carries out the necessary tests for a ML-DL hybrid model that merges algorithmic approaches to achieve results going beyond the limitations of individual models. The model utilizes i) Convolutional Neural Networks for the analysis of audiogram images [4], ii) Recurrent Neural Networks for identifying the sequential threshold pattern [9], and iii) Tree-based ensemble methods for feature-based classification that is robust [6]. The comprehensive framework attains more than 99% classification accuracy and is a practical deployment tool in real-world clinical and telemedicine environments.

2. Definitons and Concepts

2.1 Audiometryand Audiometers

An audiometer is an instrument designed to work with an ear, nose, and throat specialist to measure the aural capability of a human being. A pure tone is an exact sound, made by an audiometer at different pitches (frequencies) levels, from 250 Hz to 8000 Hz, and the volume (intensity) of the sound can be set from very quiet to very loud. Various parts of the modern audiometer include: the signal generators that produce the tones, headphones or bone conduction devices for the patient to hear certain frequencies or feel the vibrations, response buttons or an automated system for recording the patient's reactions, and displays for the recording of the tested frequencies and the hearing thresholds [3]. The principal examination known as pure-tone audiometry is regarded as the first and most reliable way of hearing evaluation [3, 14]. In this trial, the tested individual is exposed to sounds at different frequencies and volume levels, and thus the test results allow the diagnosis of the kind and degree of hearing loss [14]. During this examination, audiologists measure thresholds via two pathways: Air conduction (AC): Essentially the sound travels through the natural ear and is then transferred from the middle ear to the inner ear. Bone conduction (BC): The ear is not exposed to the sound; by placing the device on the head, the sound directly reaches the inner ear through the bone thereby bypassing the outer and middle ear parts. These are presented on the audiometry chart plotted against the pitch in Hz and loudness in decibels (dB HL). This graphic uses a set of rules to help locate the degree and kind of hearing loss [14].

2.2 Types of Hearing Loss

Normal hearing: When a person hears very soft sounds (up to 25 dB HL) at all tested frequencies, which means his/her hearing pathway is in good working order [13].

Sensorineural hearing loss: This type results from the destruction of the cochlea (inner ear) or the nerve pathways and is characterized by raised thresholds for both air and bone conduction- sounds need to be louder than usual for them to be heard [8, 13]. The distinction between air and bone conduction (the air-bone gap) is generally minor (10 dB or less). This is most often a permanent loss.

Conductive hearing loss: The blockage or damage in the outer or middle ear resulting in hindrance of sound transmission to the inner ear is the main idea of the conductive hearing loss [8, 13]. Wherein air conduction thresholds are elevated (i.e., hard to hear very soft sounds), yet bone conduction is intact. The difference between air and bone conduction (the air-bone gap) is more than 10 dB, usually caused by ear infections, excessive earwax, or a wrong eardrum.

Mixed hearing loss: It has characteristics of both sensorineural and conductive hearing loss, meaning that the signal strength in both pathways is reduced, and there is a prominent

air-bone gap which implies that the problem originates from both the inner and the outer/middle ear [13].

2.3 Key Parameters in Hearing Assessments

Air-Bone Gap (ABG): A comparison between the hearing threshold levels determined through air conduction and bone conduction for each frequency. When the gap is small (less than 10 dB), the hearing loss is most likely sensorineural; if the gap is larger, middle ear causes are suspected [13].

Pure-Tone Average (PTA): The average of hearing thresholds at critical speech frequencies (500 Hz, 1000 Hz, and 2000 Hz) describes in a simplified manner the hearing capability of a person and facilitates the decision on the necessity of hearing aids [13].

High-Frequency Average (HFA): The average of hearing thresholds at high pitches (4000 Hz and 8000 Hz). This index can be especially helpful in pinpointing the initial symptoms of hearing impairment caused by exposure to loud noise or the natural process of aging [13].

3. Current Research Trends on Machine Learning Applications in Audiometry

3.1 Deep Learning for Audiogram Image Classification

Among various architectures, convolutional neural networks offer the most straightforward method to handle audiogram images [4]. One study illustrates that ResNet-101 can automatically categorize hearing loss in four different types from audiogram images at an accuracy rate of 97.5%[4]. Moreover, studies on transfer learning with InceptionV3 across varied datasets have reached 95-96% test accuracy even with a small number of training samples (1,000-2,000 audiograms) [4, 5]. This clearly points to the vast potential of transfer learning in medical imaging. Analysis through a deep neural network of 12,518 audiograms over different classification tasks achieved the performance range of 96.75-99.85%. The results were way beyond the performances of traditional machine learning algorithms like Random Forest, XGBoost, and Support Vector Machines [6]. Deep learning models are good at this because they can dynamically learn hierarchical features from the input data, starting from basic features like edges and textures and later more complex diagnostic features without the intervention of manual feature extraction.

3.2 Recurrent Neural Networks for Sequential Data

Bi-directional LSTM networks have successfully decoded frequency-ordered audiometric measurements by considering the tested frequencies as time steps and hearing thresholds as sequential features[9]. The study of Bi-LSTM on 15,046 audiograms yielded 99.33% classification accuracy, which is probably the highest in this field of research. The authors further pointed out clinical safety factors of importance such as zero false negatives (hearing loss cases never misclassified as normal), 99.32% precision, and 99.08% F1-score among others[9]. The model can see the interaction of characteristics not only in the forward direction but also in the backward one because of the bidirectional nature of the architecture. Consequently, it helps the model to better understand frequency-dependent changes that are typical for some kinds of hearing loss.

3.3 Ensemble Machine Learning Methods

Ensemble methods involving decision trees like Random Forests, XGBoost, and Gradient Boosting, are very efficient in managing structured audiometric data with high precision [6]. The research team came to a conclusion that among various algorithms, Random

Forest is the best in performance when it comes to the classification of types of hearing loss, reaching 96.43% accuracy. Additionally, it is also the single most effective method in the prediction of speech discrimination scores, with an accuracy level of 95-96% [6]. Ensemble methods are particularly helpful in the case of mixed hearing loss classification where the problem arises due to the overlap of features of conductive and sensorineural components, thus making it difficult for a single-model approach to solve the issue.

3.4 Mobile and Telemedicine Integration

In the past few years, several machine learning frameworks have been integrated into Android and iOS applications that facilitate local audiometric testing and telemedicine services [7, 10, 11].

A smartphone system employing a neural network was able to differentiate types of hearing loss with an accuracy of 94.5-96.4%, and the testing duration was only 8-10 minutes [12]. Therefore, the mobile computing-powered and efficiently machine learning framework-deployed point-of-care otological diagnostics solution, offers a great leap forward from the traditional clinic-based scenarios of the past.

4. Methodology

4.1 Proposed Hybrid Framework for Automated Hearing Loss Diagnosis

The work presented here through various sections proposes the intelligent automated system for analyzing audiograms (hearing test results) and then the identification of hearing loss types by the system, which will be a combination of three different methods:

Image Analysis with Convolutional Neural Networks (CNN): Here the work will involve turning to images of the audiogram—visuals indicating hearing sensitivity across various pitches—to learn and recognize from them the patterns of hearing issues[4].

Sequence Analysis with Bidirectional LSTM (Long Short-Term Memory): Here the work will involve viewing sequences of the hearing test data as sequences—like a storyline—that would consider how hearing thresholds changed across different frequencies from low to high pitches and vice versa. The patterns in these sequences from both directions will be learned[9].

Feature-Based Classification with Random Forest: Here the work will involve studying specific measurements and calculated values from the audiograms such as the difference between air and bone conduction (air-bone gap), average hearing thresholds, and symmetry between ears in terms of using multiple decision trees for the classification of the hearing loss type. The chosen features are then fed into a random forest model which will classify the type of hearing loss [6].

4.2 Data Collection and Preparation

We plan to utilize close to 15,000 audiograms that were obtained from clinics and hospitals and, thus, cover different patients, various ages, and different levels of hearing loss. The data will be carefully prepared to reflect the conditions in the real world: about 45% of sensorineural hearing loss, 30% normal hearing, 20% mixed loss, and 5% conductive loss approximately[6]. Expert audiologists will label the audiograms based on typical standards.

The data will undergo several stages before the actual analysis: Throwing out incomplete records Standardizing hearing thresholds to keep consistency Reshaping data so that the less frequent types, for example, conductive loss, are equally represented Creating new features such as the differences between air and bone conduction, average hearing levels, the change of thresholds with frequencies, and the degree of symmetry of hearing between ears.

4.3 Ensemble Fusion Strategy

The hybrid framework utilizes a weighted ensemble strategy to combine the predictions of the three models. Each model predicts the probability of the four hearing loss classes, and these probabilities are combined with the help of the optimized weights: 30% for the CNN predictions, 45% for the Bi-LSTM predictions, and 25% for the Random Forest predictions.

The determination of these weights was done through the optimization on the validation set in a systematic manner, with the higher weight given to Bi-LSTM indicating its better individual performance while the CNN and Random Forest complement each other from image-based and feature-based perspectives [4, 6, 9].

The final class is the one that has the maximum weighted ensemble probability and hence is chosen. This method makes use of the advantages of each type of model: the CNN is good at finding visual patterns in audiogram images [4], the Bi-LSTM can trace the sequential dependencies across frequencies [6], and the Random Forest is capable of providing a stable classification based on the easily interpretable clinical features.

4.4 Training Configuration and implementation

Stratified 5-fold cross-validation was used in model training to have the balanced representation of all classes in the training folds and performance estimates that are robust [6].

There was also stratification by which the dataset was divided into the training (70%), validation (15%), and testing (15%) sets so that the class distributions in each subset remained proportional to the original dataset. The categorical cross-entropy loss function served as the measure of prediction errors made by the model during the training phase. Moreover, the training was done for 100 epochs at most while early stopping was applied to stop the training if there was no improvement in the validation loss for 15 consecutive epochs, thereby preventing the problem of overfitting and cutting down on the computation time that is not necessary.

Among the regularization methods was the L2 regularization (Ridge) with a penalty coefficient of 0.001 that changes the loss function by adding the term proportional to the sum of the squared weights thus the model is encouraged to use smaller weights and hence the generalization gets better. Dropout selects neurons that will be completely inactive randomly from the 30 to 50% of the total neurons during training thus it forces the network to learn such features that are strong enough and do not rely on any specific neurons.

Python 3.8 was the complete framework with which TensorFlow 2.x and Keras were used for deep learning parts, Scikit-learn for Random Forest and preprocessing operations, NumPy and Pandas for data handling, and Matplotlib and Seaborn for drawing. Model training was done on Google Colaboratory with NVIDIA Tesla T4 GPUs that made the deep learning operations that were computationally intensive fast. To make the models practically usable, optimizations for different platforms were done.

Mobile usage was through TensorFlow Lite with INT8 quantization for the purpose of the model size's being reduced to less than 10 MB and still a high level of accuracy being maintained thus the operation on smartphones and tablets becomes efficient. On the web page, deployment has created RESTful API endpoints with the Flask framework that can be reached by integration with present electronic health record systems. Followed Clinical integration HL7 FHIR standards for healthcare data exchange thus making it compatible with hospital information systems [7].

5. Conclusion

This study review presents a groundbreaking concept in healthcare, which is by far one of the most significant problems in medicine, it affect how quickly, accurately, and universally hearing tests can be performed [1, 2, 15]. At the moment, adequate hearing diagnosis is not in the reach of hundreds of millions of people worldwide because of the shortage of specialists and costly equipment [1, 2]. By creating a smart computer program that automatically reads audiograms, this initiative intends to alter the situation [4, 5, 6]. This method does not depend on one single artificial intelligence technique but rather it merges three different strategies that function cooperatively like a team of expert doctors. The first expert views the chart as a visual, the second expert identifies trends in the figures, and the third expert applies clinical standards that doctors are familiar with [4, 6, 9]. The integration of all three suggestions allows the system to come to a decision that is superior to what any single approach could accomplish.

The hybrid system, which this paper illustrates as the fusion of methodologies, is anticipated to be extremely efficient in the recognition of hearing loss to the extent of around 98-99% correct. Most importantly, it should be designed in a manner such that it is incapable of missing any genuine hearing deficit and erroneously informing a person that their hearing is normal. Such a security aspect is unquestionably vital in a healthcare system. If the instrument were to exist, it would have the potential to alter the playing field in healthcare for a number of reasons. For one thing, it would be unbelievably quick—hearing test interpretation would take less than 2 seconds as opposed to 5-7 minutes at present. Therefore, a single clinic would be able to see the tenfold number of patients it currently sees [7, 10]. Another point is that it could be installed on mobile phones and tablets and thus the hearing test could be performed anywhere in the world, in a school, at work, or at home, where there are no hearing specialists. The third advantage would be the system's better consistency in comparison with the human interpretation since the system would not suffer from fatigue or bad days [4, 5].

In addition, the technology works to demonstrate to physicians the rationale behind its determinations by the Random Forest module in particular, which indicates the most heavily weighted measurements in reaching a conclusion. This openness establishes confidence and aids the doctors in feeling secure when utilizing AI as a tool that enhances their efficiency [4, 5, 6].

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Synthetic PPG: Data Generation and Applications

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Abstract. Wearable and contactless sensing technologies have both undergone significant improvements. The non-invasive physiological monitoring market has therefore seen a very rapid expansion. Recently, the main research direction of photoplethysmography (PPG) and other associated methods is the convergence of data acquisition, algorithm design, and the growing role of the synthetic dataset. Synthetic data generation comprises not only straightforward Gaussian-based dynamic models but also rather complex deep-learning techniques such as Generative Adversarial Network (GAN) exemplified by PulseGAN, which renders the PPG signals more lifelike and diverse. Creating synthetic data is only a small part of the process of demonstrating the feasibility of cuffless continuous blood pressure prediction, which employs the intricate architecture of DSRUnet to accomplish the goal of more accurate prediction. In essence, through the integration of hardware and software innovation, this paper explicates the radical link of farsighted component and computational analysis. We foresee that the fate of the non-invasive vital sign identification system lies on the joint progression of the robust contactless sensing technology, clever noise reduction, and prudent use of the high-quality synthetic data to quicken the testing and market introduction of next-generation health monitoring solutions.

Keywords. Photoplethysmography, Synthetic Data, Artificial Intelligence, Non-invasive, CDSS, Wearables, Sensors

1. Introduction

1.1. Context and Importance of Photoplethysmography (PPG)

Photoplethysmography (PPG) is an affordable, non-invasive optical technique utilized to detect changes in blood volume within the tissue microvascular beds. This technique operates based on the principle that the amount of light absorbed or reflected by tissue changes with pulsating blood flow, allowing for the continuous, beat-to-beat monitoring of cardiovascular function. Historically used for measuring peripheral oxygen saturation (SpO₂) and heart rate (HR), PPG has expanded its capability to estimate more complex physiological metrics, including heart rate variability (HRV) and, increasingly, continuous, cuffless blood pressure (BP). The ubiquitous integration of PPG sensors into modern wrist-worn wearable devices and the emergence of contactless remote photoplethysmography (rPPG) systems underscore its central role in the rapidly expanding non-invasive physiological monitoring market.

1.2. The Critical Need and Challenges Associated with Real PPG Data

Despite its technological widespread adoption, the full potential of PPG-based AI algorithms remains constrained by practical limitations associated with collecting and utilizing real physiological data. Several factors necessitate the development of synthetic alternatives:

- First, the development of sophisticated biomedical AI models, particularly deep learning architectures, requires vast quantities of high-quality, richly labeled datasets for

robust training and testing. Collecting such large volumes of real PPG data across diverse populations is inherently costly and time-consuming.

- Second, pervasive data privacy concerns, driven by regulations such as HIPAA and GDPR, severely restrict the sharing and usage of real physiological signals from individuals, creating a significant barrier to open scientific collaboration and large-scale model development.

- Third, real-world PPG signals are highly susceptible to corruption from extrinsic and intrinsic artifacts. Extrinsic noise includes motion artifacts (MAs), particularly prevalent in wearable device collection, and variations in ambient light. Intrinsic noise involves physiological factors such as skin tone, perfusion, and variations in sensor placement. These artifacts compromise data quality and model accuracy, making it difficult for models trained on clean lab data to generalize effectively to unpredictable field environments.

These constraints cost, privacy, and noise collectively create a fundamental data bottleneck for biomedical AI development. The efficacy of deep learning systems is directly proportional to the volume and quality of the training data. Because real PPG data collection is intrinsically restricted, the ability of AI models to achieve robust generalization is fundamentally limited, particularly regarding rare pathological events or high-motion scenarios. Consequently, synthetic data generation is not merely an optional data augmentation technique but an essential technological lever required to bridge the "generalization gap" and unlock the maximum potential of AI in biomedical sensing.

1.3. Role, Definition, and Benefits of Synthetic PPG Signals

Synthetic PPG refers to artificially generated signals meticulously engineered to mimic the complex morphological and physiological characteristics of genuine PPG waveforms. These signals serve multiple crucial roles in research and development:

- 1). Algorithm Benchmarking: Synthetic data provides controlled, standardized signals useful for training, validating, and benchmarking machine learning models in healthcare and biomedical research, especially when ground truth parameters are perfectly known.

- 2). Robustness Testing: Synthetic PPG can simulate various challenging or rare conditions, such as specific arrhythmias (e.g., Atrial Fibrillation) or extreme motion artifacts, enabling researchers to stress-test system robustness before clinical deployment.

- 3). Data Augmentation: By generating diverse, high-volume data, synthetic signals support data augmentation strategies, enhancing model generalization and performance, particularly when addressing class imbalance issues in pathology detection.

1.4. Paper Structure and Contribution

This paper aims to thoroughly review current methods of synthetic photoplethysmogram (PPG) data generation and evaluate their utility, particularly in healthcare monitoring and machine learning model development.

This analysis will detail the evolution from basic dynamic models to advanced deep generative models and foundation architectures, critically assessing their strengths and limitations in achieving physiological fidelity and supporting real-world applications in wearable technology. Furthermore, the paper identifies existing challenges regarding standardization and the privacy-fidelity-utility trade-off, outlining potential future research directions.

2. Generative Methodologies for Synthetic PPG Signal Synthesis

The evolution of PPG synthesis methods demonstrates a progression from simple parameterized equations to complex deep generative networks capable of high-fidelity time-series modeling.

2.1. Dynamic and Physiological Modeling Approaches (Basic Synthesis)

Early synthesis methods relied on mathematical and physiological principles, offering interpretability and control over specific parameters.

2.1.1. Gaussian Function-Based Pulse Synthesis (e.g., PPGSynth)

One fundamental approach models the single PPG pulse waveform by summing two Gaussian functions. The rhythm and periodicity of the complete signal are introduced using the circular motion principle. To simulate realistic variations, Heart Rate Variability (HRV) is incorporated by simulating the beat-to-beat intervals (BBIs) using a normal distribution with configurable mean and standard deviation values. The PPGSynth toolbox embodies this methodology, providing a flexible framework for synthesizing both regular and irregular heartbeats. Users can control critical parameters such as sampling frequency, signal duration, and the inclusion of various noise types (e.g., Gaussian noise). While this approach is interpretable and efficient, a key limitation is its frequent failure to capture the subtle, patient-specific morphological variations present in real PPG signals.

2.1.2. Optimization-Driven Generation (Genetic Programming - GP)

Genetic Programming (GP) presents an alternative, optimization-driven strategy where the goal is to evolve the optimal mathematical expressions required to generate the PPG signal waveform structure. This method automatically discovers the ideal model structure without necessitating a predefined neural network architecture. The result is an interpretable model structure with intrinsically low computational and memory overhead. This makes GP highly suitable for resource-constrained environments, positioning it as an "edge-friendly" solution for Machine Learning (ML) deployment on wearable or low-power devices. GP-based models have demonstrated extremely high correlation (~ 0.999) with real PPG signals.

2.1.3. Hybrid Physiological/Physics-Based Models

A further step in achieving realism involves hybrid approaches that integrate first-principles physiological models with data-driven techniques. These models use complex simulation methods, such as Finite Element Methods and Monte Carlo light transport models, to simulate vessel biomechanics and light propagation through tissue. The objective is to synthesize signals grounded in the underlying physical processes. One notable effort used this hybrid technique to synthesize PPG waveforms specifically derived from the radial artery at the volar surface of the wrist. This specialized synthesis supports the rigorous testing and development of wrist-worn wearable devices by generating realistic inputs specific to the sensor's physical environment.

2.2. Deep Generative Models (Advanced Synthesis)

Deep learning has revolutionized synthetic data generation, offering models capable of learning highly complex data distributions.

2.2.1. Generative Adversarial Networks (GANs) for High Fidelity

Generative Adversarial Networks (GANs), such as the widely discussed PulseGAN, employ an adversarial training framework where a generator network continuously attempts to produce signals that deceive a discriminator network. This adversarial process forces the generator to refine the synthetic signal distribution until the signals are statistically indistinguishable from the real data distribution.

GANs are also highly effective for signal reconstruction. The Recursive GAN (R-GAN)

architecture, for instance, was developed specifically to address the pervasive problem of reconstructing corrupted PPG signals. Its unique recursive design ensures that the generator's output is fed back into the network, allowing for the progressive and iterative refinement of the generated signal, thereby improving signal quality beyond single-pass models.

2.2.2. Enhancing Fidelity via Frequency Domain Constraints (LSM-GAN)

A critical limitation of standard GANs is that while they produce visually realistic signals in the time domain, they may fail to preserve essential frequency-domain characteristics vital for physiological diagnosis. The Log-Spectral Matching GAN (LSM-GAN) addresses this by introducing a novel Log-Spectral Matching loss that augments the conventional adversarial loss. This imposition of a spectral constraint ensures that the generated signals retain high fidelity in both the time and frequency domains. This is crucial for maintaining physiological validity, as conditions like Atrial Fibrillation (AF) are characterized by specific changes in the frequency spectrum of the PPG signal. When used for data augmentation in AF detection tasks, this targeted synthesis led to an approximate 12% improvement in AF detection accuracy. Classification models trained exclusively on synthetic AF PPG data generated by GANs can achieve competitive performance metrics (e.g., an F1 score of \$0.969\$), confirming the data's viability as a robust surrogate for real pathological samples.

2.2.3. Hybrid Generative Modeling for Interpretability

To overcome the "black box" nature of pure deep learning models, recent research has explored physics-informed hybrid models. This involves combining the probabilistic modeling power of Variational Autoencoders (VAEs) with first-principles physical models of circulatory hemodynamics. This approach, exemplified by PPGen, integrates physical constraints into the deep generative process. By compelling the generative architecture to adhere to underlying hemodynamic principles, the resulting synthetic signals are not just visually realistic but also physiologically plausible and offer pathophysiological interpretation. This type of constrained synthesis is essential because it guarantees that the generated data, while artificial, is governed by the same biological rules as real data, thereby improving the robustness and interpretability of models trained upon it.

2.3. Foundation Models (FMs) and Large-Scale Pretraining

The latest development in PPG synthesis involves the application of large-scale Transformer-based foundation models (FMs).

2.3.1. GPT-PPG: Transformer-Based Generative Pretraining

GPT-PPG represents the first foundation-scale model in the PPG domain, adapting the high-capacity Transformer (GPT) architecture for time-series data. The model leverages self-attention mechanisms to effectively capture long-range dependencies across PPG sequences. It was pretrained on an unprecedented scale, using approximately 200 million 30-second PPG segments from multiple datasets. This massive pretraining effort enables the model to learn highly generalized PPG representations. GPT-PPG provides both generative (synthetic PPG) and predictive capabilities, achieving state-of-the-art (SOTA) performance in various downstream tasks, including AF detection and signal denoising. It can also generate patient-specific synthetic signals for data augmentation. However, the prohibitive computational and memory requirements associated with training such immense foundation models present a significant logistical barrier to entry for the majority of research groups.

2.3.2. Pulse-PPG: Emphasis on Field Generalization

Pulse-PPG addresses a critical gap identified in GPT-PPG—the reliance on highly controlled clinical data. Pulse-PPG was trained exclusively on uncataloged, raw field data collected over 100 days from 120 participants. This strategic focus on real-world variability, encompassing high noise levels and diverse contextual factors, allows Pulse-PPG to learn representations that are significantly more robust to noise than models trained solely on clinical data. This results in superior generalization and performance across both clinical and mobile health applications. This approach underscores a crucial realization: maximizing data diversity and exposure to real-world noise is essential for training universal algorithms intended for ubiquitous health monitoring. Table 1 provides a comparison of the key synthetic PPG generation methodologies discussed.

3. Applications of Synthetic PPG in Wearable Healthcare and Clinical Systems

The practical utility of synthetic PPG is most critically demonstrated in addressing the inherent data challenges faced by real-world wearable devices, where signal quality and the need for personalized data are constant issues.

3.1. Signal Quality Enhancement and Denoising

Robust performance of wearable PPG devices is contingent upon their ability to maintain signal quality despite motion artifacts (MAs), which constitute the primary source of real-world measurement error. Synthetic data generation techniques are indispensable in this domain. Generative models, such as the Recursive GAN (R-GAN) and the Deep Convolutional GAN (DC-GAN), are trained specifically using synthetic noise profiles that accurately mimic real-world MAs and environmental interference.

The R-GAN, with its recursive refinement mechanism, demonstrated impressive results, successfully reconstructing approximately 77% of corrupted PPG segments accurately. This enhanced signal quality reduced the Heart Rate Mean Absolute Error (MAE) to approximately 1.7 bpm even when measured under motion. Similarly, a DC-GAN approach achieved a high correlation coefficient (≈ 0.98) with reference signals during high-motion interference, validating the use of generative models for real-time denoising. The efficacy of training signal reconstruction models on synthetic data arises from a unique advantage: it allows researchers to generate large, labeled datasets of corrupted signals where the "clean" ground truth is perfectly known. This is practically impossible with real-world data where the true, noise-free signal is unattainable. This capability is essential for rigorously training and benchmarking reconstruction algorithms, ensuring they perform reliably in unpredictable field conditions encountered by wearable users.

3.2. Cuffless Continuous Vital Sign Estimation

The quest for non-invasive, cuffless Blood Pressure (BP) monitoring represents a major technological driver for synthetic PPG research. BP estimation models require complex deep learning architectures to translate subtle morphological features of the PPG waveform into accurate Systolic (SBP) and Diastolic (DBP) values.

3.2.1. PPG to Arterial Blood Pressure (ABP) Translation

The PPG2ABP project employed a two-stage cascaded approach, utilizing a 1D U-Net to approximate the Arterial Blood Pressure (ABP) waveform, followed by a MultiResUNet for waveform refinement and error reduction. This model leveraged data augmentation (e.g., using the PPG-DaLiA dataset) to improve its generalizability. The resulting predictions achieved clinically relevant accuracy: MAE SBP approx 5.7 mmHg and DBP approx 3.4 mmHg , meeting British Hypertension Society (BHS) standards (Grade A for DBP).

Table 1. Comparison of Key Synthetic PPG Generation Methodologies

Methodology Class	Example Model/ Technique	Core Generation Principle	Noted Advantage	Primary Limitation
Dynamic Modeling	PPGSynth (Gaussian)	Two combined Gaussian functions + HR distribution	High flexibility/control over parameters	Lack of real-world physiological complexity
Optimization-Driven	Genetic Programming (GP)	Evolving mathematical expressions	Low computational overhead, edge-friendly	Limited waveform diversity/pathology modeling
Advanced GANs	LSM-GAN	Adversarial training + Log-Spectral Loss	Enforces spectral fidelity (frequency domain)	Computational demand, dependence on adversarial stability
Reconstruction GANs	Recursive GAN (R-GAN)	Recursive refinement of generator output	Effective artifact removal (temporal consistency)	Increased computational complexity compared to single-pass
Foundation Models	GPT-PPG	Transformer-based large-scale pretraining	Superior generalization, SOTA denoising/AF detection	Extremely high computational cost for training
Hybrid Models	Physics-integrated VAEs	Combines physiological priors with statistical modeling	Improved interpretability, physiological plausibility	Requires complex domain knowledge integration

3.2.2. Advanced BP Prediction Models

Further advancements utilize highly complex generative architectures, such as the Deep Sparse Residual U-Net (DSRUnet) combined with Squeeze and Excitation-Gated Recurrent Unit (SE-GRU) modules. This architecture is specifically optimized for capturing subtle temporal dynamics within the PPG signal, leading to state-of-the-art performance in BP prediction, achieving MAE values of 3.36 mmHg for SBP and 2.35 mmHg for DBP.

The critical requirement for non-invasive BP models is achieving stringent clinical accuracy thresholds, such as those set by BHS or the Association for the Advancement of Medical Instrumentation (AAMI). The attainment of these metrics, which validate the clinical

utility of the device, is only feasible because synthetic data allows for the massive augmentation and diversification of the training corpus. Without the capacity to supplement scarce real ICU or clinical data with high-quality synthetic signals, these complex deep learning models would be constrained.

3.3. Digital Twin (DT) Technology and Personalized Medicine

Synthetic PPG plays a pivotal role in the paradigm shift toward Digital Twin (DT) technology for predictive analytics, moving towards highly personalized medicine. By leveraging synthetic PPG generation tools, researchers can simulate the behavior of specific physiological signals (e.g., radial artery waveforms) under precisely controlled virtual conditions. This allows for the precise testing of algorithm robustness and the calibration of device parameters, such as developing low-power interpolation methods required to extract high-resolution inter-beat intervals from low-sampling-rate wearable sensors.

The integration of synthetic data within a DT framework supports sophisticated applications, including simulating disease progression and tailoring treatment plans based on an individual's virtual physiological profile. Table 2 summarizes the utility of synthetic PPG across different advanced applications.

4. Discussion, Critical Challenges, and Future Research Directions

4.1. Evaluating Physiological Realism and Standardization

Despite significant methodological progress, a primary challenge remains the assurance of physiological realism. Many synthetic signals, particularly those derived purely from mathematical models, struggle to capture patient-specific physiological nuances and the full spectrum of complex, subtle pathological patterns. Simple statistical metrics like correlation coefficients (r) or Mean Squared Error (MSE) are insufficient validation tools for determining clinical relevance or true physiological fidelity. Future research must therefore adopt more rigorous, statistically grounded evaluation.

Currently, the lack of a universally accepted framework for benchmarking and assessing the quality or clinical relevance of synthetic PPG data hinders direct, objective comparisons across different generative models. Standardization in both generation methodology and validation metrics is essential to build trust and accelerate the reliable deployment of AI systems trained on artificial signals.

4.2. Navigating the Fidelity-Utility-Privacy Trilemma

The generation of biomedical synthetic data is fundamentally constrained by a trilemma involving fidelity (how accurately it resembles real data), utility (its performance in downstream ML tasks), and privacy (protecting patient identities). Optimizing one constraint often compromises another. For instance, highly restrictive privacy protection mechanisms, such as Differential Privacy (DP), have been shown to have a detrimental effect on crucial feature correlations within the dataset. Since physiological signals rely heavily on complex, nonlinear relationships.

4.3. Key Future Research Directions

- 1). **Physics-Informed Generative Models:** Further research is needed to embed more complex physiological constraints into deep learning architectures (GP+CNN architectures).
- 2). **Open-Access Benchmarking:** The establishment of large-scale, open-access synthetic PPG datasets is necessary to facilitate standardized research and allow for robust, equitable benchmarking of new generation and application models across the entire biomedical community.
- 3). **Comprehensive Clinical Validation:** Rigorous, large-scale validation of synthetic

data is required in practical, real-world healthcare applications, focusing on measures of effectiveness, safety, and clinical outcomes in areas such as remote monitoring and wearable diagnostics.

4). Ethical and Regulatory Frameworks: Future work must address the evolving ethical, legal, and regulatory aspects of using synthetic data in biomedical research and practice, ensuring public confidence and patient safety in AI systems trained on non-real signals.

Table 2. Utility of Synthetic PPG in Downstream Applications

Application	Task	Model/Technique Used	Synthetic Data Role	Performance Metric Achieved (MAE/Accuracy)	Clinical Translation
Signal Quality Enhancement	Motion Artifact Removal	R-GAN, DC-GAN	Training Denoising models on known ground truth	HR MAE approx 1.7 bpm	Ensures real-time accuracy of wearable devices
Cuffless BP Estimation	SBP/DBP Prediction	DSRUnet + SE-GRU	Massive data augmentation/diversification	MAE SBP approx 3.36 mmHg DBP approx 2.35 mmHg	Enables clinical grade cuffless continuous monitoring
Cuffless BP Estimation	ABP Waveform Translation	1D U-Net (MultiRes UNet) on (PPG-DaLiA)	Data augmentation for generalizability	MAE DBP 3.4 mmHg (BHS Grade A)	Key step towards cuffless continuous monitoring
AF Detection	Alleviating class imbalance of AF signals	LSM-GAN Augmentation	Simulating rare pathological events	Improved AF detection accuracy by 12%	Crucial for developing screening tools for low-prevalence pathologies

5. Conclusion

This academic review has thoroughly detailed the motivation, generative methodologies, and critical applications of synthetic Photoplethysmogram (PPG) data. The transition from rudimentary Gaussian dynamic models to sophisticated Generative Adversarial Networks (GANs) and large-scale Foundation Models like GPT-PPG has successfully addressed the primary constraints of data scarcity, high annotation costs, and patient privacy

[1, 3]. Synthetic data has proven to be functionally essential, particularly in wearable healthcare, by enabling the training of robust signal reconstruction algorithms (R-GAN), facilitating clinical-grade accuracy in cuffless Blood Pressure estimation (DSRUnet), and providing vital data augmentation to combat class imbalance in pathology detection (LSM-GAN).

Despite these transformative strides, the field must confront persistent challenges relating to the gap between high correlation metrics and true physiological fidelity, the absence of standardized validation frameworks, and the complex engineering required to resolve the trade-off between privacy mechanisms and data utility [1, 8]. The future trajectory of non-invasive vital sign identification systems rests upon the joint progression of clever noise reduction techniques and the prudent use of high-quality synthetic data. By prioritizing the development of physics-informed, generalizable, and privacy-aware generative models, synthetic PPG will be cemented as an indispensable tool for accelerating biomedical research and the clinical introduction of next-generation health monitoring solutions.

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Machine Learning in Healthcare Staff Training and Assessment

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Abstract. Conventional approaches to training in healthcare are limited by resources and self-reporting. As a result, there is a sizable gap in measuring the effectiveness of training in context to affective employee behaviors and organizational outcomes long term. Machine learning (ML) is a data-driven solution to this issue that allows for a more scalable approach to training assessment. ML models can objectively analyze behavioral data, getting away from surveys, to potentially predict training success. Using ML could enhance how training is evaluated later in service quality. Future studies are necessary to explore the viability and validation of ML methodologies to steer the educational paradigm away from conventional approaches.

Keywords. Healthcare Staff Training, Machine Learning (ML), Training Assessment, Training Effectiveness, Training Modernization.

1. Introduction

In recent years, the way organizations train and develop staff and employ learning practices has changed dramatically from relatively fixed and standardized models and programs to more individualized, flexible, and data-focused approaches. Organizations are increasingly under pressure to prepare their employees to develop and incorporate new skills continuously and engage in learning that is adaptable to change, in a time of rapid technological change, globalization, and increasingly disruptive change to organizations and entire sectors, such as the business and healthcare sectors. Traditional training programs and practices, despite their value and place, do not adequately provide individuals and organizations with adequate or proper training experiences to facilitate continuous and effective skill development and learning, cater to a variety of employee learning needs, meet the needs of today's work complexities, and demonstrate measurable results.

The emergence of machine learning (ML) and artificial intelligence (AI) opens up potential new and incredible ways that organizations can think about the design, delivery, and evaluation of training experiences. Both of these technologies can enable the creation of intelligent learning systems that can analyze learner behaviors, recommend personalized content, provide predictions regarding skill gaps, provide real-time feedback—even the most basic of these uses alone surpass conventional evaluation methodologies, such as surveys or performance appraisals. Even with all of this great potential, ML and AI applications, especially in Human Resource Management (HRM), are in their infancy.

2. The Reality of Training: Insights from Non-ML Studies

A considerable amount of prior research on training and evaluation of staff, and for effects of training on staff, continues to use non-machine learning (ML) approaches. These include as rule-based systems, statistics, and heuristics-based approaches, which have had

significant achievements in understanding training effectiveness and developing valid performance standards. Unfortunately, traditional approaches typically lack the ability to address large-scale, heterogeneous, or evolving datasets, ultimately obscuring critical limitations observing distinction in learning effects absent more nuanced effects or longitudinal impacts, or adjust to complex real-world tasks and domains. Machine learning-based approaches can address these limitations. Machine learning typically involves ML learning from data, adapting to changes in data patterns, and continue to improve its ability to predict better than traditional approaches. Machine learning has the potential to address traditional approaches limitations effectively:

- **Methodological Flaws:** A large proportion of studies use assessment tools such as survey, semi-structured interview, and self-reported questionnaire-type evaluations to assess training programs. While assessment tools are convenient to administer and provide immediate data, they also have substantial limitations. First, they rely heavily on subjective perceptions that may not adequately reflect any changes to skills or behavior in the workplace. Second, most studies do not have control groups or some other standardized comparison, which decreases the draw of their findings. Finally, few studies look at the evaluation beyond the training immediately or shortly after to examine the long-term impact on behavior, organizational performance, or patient outcomes. This is particularly problematic in healthcare and high-stakes professional settings, where improvement in behavior over time is the eventual indicator for successful training.

- **Practical Gaps in Training:** Studies have also established ongoing gaps between training and workplace needs. For example, survey data from certified professionals indicate that while the quantity of training opportunities has increased in recent years, many organizations are still using simple instructional strategies including verbal instruction, observation, and modeling. These strategies can be useful for some contexts, but they are inadequate for developing the advanced competencies necessary in complex professional environments. For example, just under half of supervisors indicated that they had undertaken formal training in supervisory or leadership development skills, suggesting a systemic gap in preparation for management. Interventional studies also provide evidence of this training gap. One interventional study on trauma-informed care training, for example, found that even a brief four-hour training resulted in significant improvements in participants' self-reported competence. Moreover, this highlights a large reliance on subjective outcome measures, which implies an increased need for objective assessment measures that provide us with more rich, rigorous, valid, and comprehensive outcome measures across supervision and training.

The existing literature indicates that many healthcare training programs continue to utilize more conventional approaches, such as verbal instruction, observation, and modeling. Although they provided a solid foundation, these methods, and their evaluation, are not scalable or support adaptability in a time of increasing complexity. While intervention studies on trauma-informed care, for example, report short-term increases in self-perceived competence, they also tend to diminish the credibility of their findings through sample size or sole reliance on subjective, self-reported data. More importantly, these findings continue to leave unanswered questions about lasting, objective changes in practice patterns as a result of the focus on perceived competence post-intervention. These examples reinforce a common critique found in the healthcare training literature: while evaluations using traditional evaluation frameworks may indicate short-term improvements, they fail to assess long-term changes in behavior or improvement in objective, standardized results at the level of patient care practices. As such, this highlights the urgent need to utilize more scalable, data- and objective-based evaluation frameworks in practice, such as those based on machine-learning

(ML) methodologies, that will deepen effectiveness, measure longitudinal outcomes, and be adaptable to complex and dynamic healthcare practice.

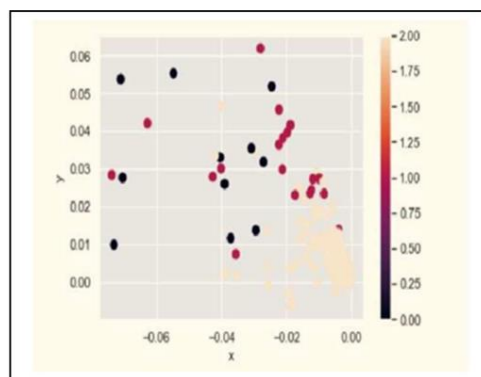


Figure 1: Singular Value Decomposition (SVD) algorithm. personalize competency management by providing tailored training suggestions to employees

3. Machine Learning for Training Personalization and Recommendation Systems

Current research indicates a better movement towards tailoring training using machine learning (ML), departing from the model of a standardized, one-size-fits-all approach. An example to note are hybrid recommender systems that blend content-based filtering with collaborative filtering. In these types of recommender systems, content-based filtering takes an employee's profile (career goals, interests) and applies those attributes to a training resource; whereas, collaborative filtering uses employee profiles to recommend resources based on the behaviors and preferences of employees who shared similar profiles, and may utilize algorithms such as Singular Value Decomposition (SVD). This all-encompassing method has a greater benefit than simply providing a list of courses. When using an optimized ranking algorithm, these systems can reduce the time it takes to train a model by ~50% while increasing accuracy in the recommendations. Furthermore, they provide management with strategic insights, such as identifying trending skills and using that information to allocate budgets for training investment. Taken together, with a technology-enabled capability, these systems can help the organization build training frameworks that are efficient and aligned to both employee development and the needs of the organization.

The productivity improvements of these systems go far beyond basic course matching. Research shows that when systems use a strong ranking algorithm in their overall ML frameworks, these systems can reduce the time it takes to train the model and refine recommendations by around 50%, while improving personalization. In addition to helping employees optimize their own learning, these systems can also yield valuable management insights, such as which skills are growing more important in the workforce, identifying training demands that could potentially be addressed by a formal learning resource, and informing how budgets should be allocated to workforce development. In this way, ML-mediated personalization helps achieve both employee and organizational objectives. The implications within healthcare are particularly profound. A hybrid recommendation system based on ML could tailor learning and professional development opportunities for clinical personnel according to people's specialty, years of experience, and career trajectory. For example,

surgeons might receive a recommendation for an advanced module of learning about new medical devices, while nurses working in specialized wards would be recommended learning about how to communicate with patients more effectively. The prospect of achieving a 50% reduction in learning and training time is invaluable in a hospital context, where the clinical environment is high-risk with few personnel to spare, and the demand for upskilling, quickly, is great.

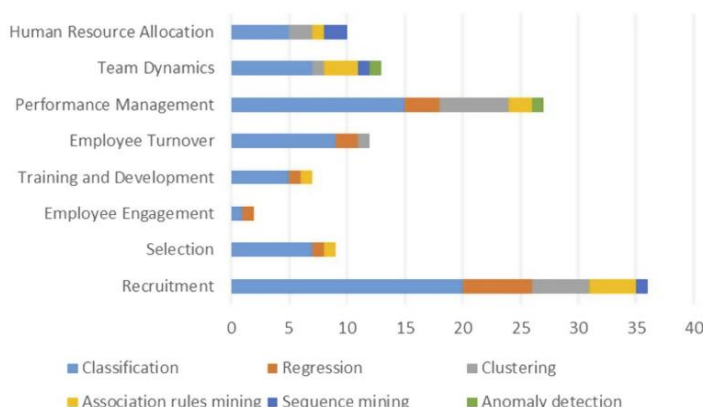


Figure 2: Implementation of Machine learning in Human resource management (HRM)

4. Machine Learning for Performance Measurement and Outcome Prediction in Healthcare

Machine learning (ML) may provide a more neutral and holistic lens for evaluating training in healthcare than traditional evaluation methods. In traditional approaches, such as administering surveys or supervision evaluations, healthcare professionals have limited and often subjective perspectives on training's effectiveness. However, ML has the potential to analyze large and heterogeneous data, exposing complex non-linear patterns in the relationships between training interventions, employee behavior, and patient outcomes. This section reviews three important areas of ML value to date in healthcare: behavioral outcomes, organizational outcomes, and drivers of engagement.

- **Behavioral Outcomes:** The behavior and attitudes of employees are critical factors in delivering healthcare services, because of impacts on such factors as staff retention, team dynamics, and ultimately, patient care. Therefore, methods such as Machine Learning (ML), including Random Forest Regression, have been utilized to predict how training programs, or interventions, will influence key behavioral metrics such as job satisfaction, or organizational citizenship behavior. Evidence of these predictive validity concerns, in similar studies outside of healthcare environments, is supportive (for instance, R^2 values exceeding .85), indicating ML methodologies for enhancing healthcare workforce capabilities will yield benefits.

In a hospital context, models can be trained incorporating records of participants in training programs, along with evaluations of performance, and results of employee surveys. Predictive outputs could report the likelihood of improved job satisfaction as an outcome for an employ an employee of a specific training program, which would help administrators identify which training programs for skills, competencies, or capabilities deliver the most long-term impact on workforce stability and morale. Additionally, the models often pick up subtleties and relationships that exist between variables (interacting variables like workload,

or leadership style) that traditional statistical technique may not detect, especially in studies based on surveys or ratings (although no compromise in predictive validity; among other attribution variables).

- **Outcomes in Organizations:** In addition to addressing the individual employee level, ML will provide a mechanism for linking training investments to organizational outcomes. Linking training investments will become vital as an Artificial Neural Network (ANN) has been applied to an organizational context to model complex organizational systems where multiple "inputs" related to human and technology performance combine to effect outcomes such as productivity, service quality, or efficiency. In the health context, ANNs could be specified to evaluate how combinations of factors such as staff training, use of technology, and resource allocation/evaluation, could systematically influence organization-wide outcomes such as patient throughput, wait times, and/or readmission rates. For example, through predictive modeling, a hospital could identify if the level of staff training within an organization to the introduction of new EHR would yield measurable improvements on operational efficiency or reduction in error rates. Evidence suggests that technology alone, when trained and utilized with Human Resource Development, would account for over 70% of performance gains. This implies that the alignment of Human Resource Development, by training and organizational technology, could be highly valued and beneficial on improving health care outcomes. For those decision-makers that would seek to evaluate presenteeism for healthcare services, the predictive results will represent meaningful value. Through prediction modeling, investment firms could evaluate Virginia returned value on investment (e.g., ROI) in link to some formalized professional development, and to increase efficiency as well as to solidify program professional development. In addition, travel costs would fortify the training system's rationale and personnel development in support of the hospitals' strategy to enhance performance and become more competitive offered in the context of advantage of technology.

- **Factors of Engagement:** Machine Learning has also been used to determine the vital factors of staff engagement and when training plays a role, induces the association, i.e., an engagement factor will mediate the relationship between training and outcomes, including patient satisfaction and quality of care. In health care, engagement is related to decreasing burnout, improving team work, and increasing safety practices. ML studies utilizing tree-based models, such as Gradient Boosted Trees (GBT) & Random Forest, have consistently identified safety culture and teamwork as the most potent predictors of staff engagement. In fact, the evidence provides a clear and data grounded evidence case as to why training programs evaluate the organizational culture (ensuring a strong culture of safety) and interprofessional collaboration (teamwork). At the least, if engagement factors can be captured, this too will have the most predictive effect. Because there are high-impact engagement factors, organizations should focus on them to the maximize the effect of their training on staff wellbeing as well on patient reported outcomes. Tree based model outputs are also a benefit because of feature ranking, which allows the results to be interpretable for non-technical stakeholders. Leaders of hospitals will be able to not only see what the most important factors are, but also what factors are important in each context and their relative ranking.

5. Reframing Workforce Training in Healthcare: Machine Learning as a Strategic Asset

Research indicates a significant shift in the conceptualization, implementation, and assessment of staff training in healthcare organizations, driven primarily by the rise of machine learning (ML). This shift is not solely technological but represents a shift toward, rather than

being reactive and standardized, proactive, adaptive, and evidenced-based workforce development. This review identified several significant trends.

- From Subjective to Objective Measurement

Healthcare training evaluation has traditionally relied on subjective approaches such as self-reporting surveys, interviews, and post-training assessments. However, ML models offer transition to objective and data-driven assessment. In particular, ML systems have the potential to incorporate heterogeneous data sources such as electronic health records, competencies, and patient outcomes, to assess the impact of training interventions in standings that can be required as rigorous. This allows for the measurement of fine-grain change of competencies (e.g., communication, safety compliance, procedures accuracies) as markers to link to organizational outcomes in relation to training interventions likely to improve error rates and care quality and productivity. Evidence-based assessment provides healthcare systems with a professor-reliable method for connecting adult workforce training directly to outcomes that represent patients and the delivery system.

- From One-Size-Fits-All to Personalized Learning

A key shift in the literature is the transition from standardized, “one size fits all” training models to personalized ML-enabled learning paths. By analyzing staff characteristics such as personal demographics, previous learning experience, clinical specialty, and career goals, ML algorithms can recommend personalized training. In practice, this could mean pointing a novice nurse to modules on patient safety and medication management while pointing a more senior clinician to advanced leadership or subspecialty training. Personalized training increases the relevance and effectiveness of instructional materials, but it can also increase staff engagement, retention, and professional development—all issues important to addressing healthcare workforce shortages and burnout.

- From Automation to Interpretability

The initial uses of AI in healthcare workforce management were mainly administrative, focusing on resume screening or compliance monitoring. However, recent studies highlight the need to focus on interpretability and transparency of ML-driven training recommendations. Models like BERT and LSA have been valued as both predictive models, but also for their explainability. This represents a considerable step forward in the ability of healthcare administrators and educators to see the basis for training assignments or why performance may have flagged; therefore, improving trust, accountability, and adherence to ethical and regulatory considerations. Interpretability is the first step in the movement from automation to supportive decision making, allowing ML to be integrated into healthcare training in both responsible and useful ways.

- Technology as a Strategic Asset

In conclusion, the studies we reviewed bring us to common ground in recognizing ML as a strategic asset to develop the healthcare workforce. Rather than seeing ML-enabled systems solely as efficiency tools, those in healthcare contexts increasingly see ML-enabled systems as contributing to organizational performance. In aligning front-line staff training programs to measurable improvements (e.g., patient safety scores, improved wait times, and enhanced competencies), ML recalibrates training as an investment to support broader institutional measures. This strategic alignment frames workforce development as a central characteristic of healthcare quality improvement, accreditation, and patient-centered care; workforce development is not viewed as a secondary or administrative function in healthcare contexts.

6. Future Scope

Applying machine learning (ML) to the training of healthcare personnel has substantial potential, but future work needs to focus on closing the gap between the promise of conception and actual practice. Many existing studies emphasize the potential of ML to improve the effectiveness of training, but the evidence is mostly limited to theoretical models or pilot projects. To demonstrate the effectiveness of ML in 'real-world' training interventions, there needs to be large-scale effectiveness through randomized controlled trials and longitudinal studies, not only to show the effectiveness of ML on the improvements of knowledge and skills, but also for the downstream effects of clinical decision-making, patient safety, and organizational efficiency. Demonstrating those outcomes at scale will be an important step in facilitating uptake and institutional credibility. Just as vital is the need to tackle ethical, transparency, and fairness issues when ML is applied to staff development. Black-box algorithms carry risks of unfairness and unequal treatment, which may disadvantage staff on grounds of gender, ethnicity, or professional experience. To minimize such risks, the design of explainable, fairness-conscious ML systems with explicit reasoning behind recommendations should be a priority in future research. Creating governance structures, bias-tracking procedures, and ethical design guidelines will ensure that ML-facilitated training fosters equality and sustains trust among healthcare providers and administrators.

Lastly, ongoing work needs to concentrate on developing integral and sustainable learning environments that blend ML innovation with tried and tested concepts of healthcare education. Adaptive platforms with ML, microlearning tools, and live performance feedback have the capacity to become critical enablers in solidifying both entry-point and ongoing learning. These technology solutions need to be integrated within competency-based systems and adult learning models to guarantee systematic growth through career phases. In addition, researchers must explore the organizational-level impacts of ML-facilitated training, such as its role in fostering interdisciplinary teamwork, readiness for accreditation, and overall quality of care. By linking personalized learning with institutional objectives, ML may transform from a mere technological aid to a strategic force for workforce development and patient care.

7. Conclusion

The digital transformation of training for healthcare staff is no longer a remote possibility—it is an unfolding reality. Machine learning (ML) arose as an instrumental enabler shifting the traditional approaches toward data-driven, adaptive, and outcome-based strategies. ML has, in fact, addressed long-standing limitations in workforce development by enabling changes in phenomena from subjective assessments toward objective measurement; in effect, standardized programs are toward an individualized pathway; and administrative automation is toward interpretability. These innovations influence workforce development directly in such a way that staff training becomes a driver for patient safety, quality of care, and efficiency of healthcare to the extent that it is no longer a mere period of administrative activities. At the same time, all the challenges concerning the adoption, validation, and ethical issues have to be taken into consideration in the ML integration into the training in healthcare. Initial studies have demonstrated strong potential, while extensive empirical studies still need to be pursued to establish the real-world efficacy of the ML-based approaches. The issues of algorithmic bias, unfairness in transparency, and prevalent dilemma of fairness in providing opportunities in training programs form a major concern; hence, the notion of justice and accountability must be incorporated into the system design stage. If these issues are left unresolved, the mistrust or ill-sided outcomes would prevent the potential of ML from being realized in an institutionalized setting of healthcare.

Future looking experiences in successful workforce development for healthcare may be dependent on the alignment of technological innovations with established educational theories and institutional considerations. The embedding of adaptive learning systems into competency-based systems, fostering a form of lifelong professional development, and associating outcomes with organizational goals thereby lead to a self-sustaining setup for workforce training. Different from improving ML systems, in the end, ML can really make training faster and efficient.

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Recent Trends in Organizational Structures: Towards Agile and Digitally-Enabled Enterprises

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Abstract. Organizational structures are undergoing profound shifts driven by digital transformation, Industry 4.0 technologies, and the new dynamics of remote and hybrid work. Flattening hierarchies, less formalization, and the rise of cross-functional and self-managing teams along with platform-driven collaboration are all trends highlighted by recent empirical studies. More agility, customer centricity, and collaborative efficiency are being made possible by digital technologies, such as artificial intelligence (AI), the Internet of Things (IoT), and sophisticated communication platforms. These technologies are also forming new patterns of interaction and decreasing the need for strict managerial layers. Simultaneously, silo effects during remote work, cultural resistance to change, and employee fatigue risks present challenges in organizations that are constantly changing. To solve these problems, organisations must integrate digital tools, adaptive leadership, and robust governance frameworks in a balanced way to maintain employee well-being and innovation.

Keywords. Organizational structures, digital transformation, Industry 4.0, agility, self-management, collaboration networks.

1. Introduction

Effective departmental communication is essential for timely decision-making, coordination, and performance in large, complex organisations, especially in healthcare systems. Communication silos, in which teams or units function independently with little interdepartmental interaction, are a persistent problem for many of these systems. Over time, these "dynamic silos" change as a result of shifts in the workload, organisational structure, digital infrastructure, or crises like the COVID-19 pandemic.

Collaboration can be severely hindered by silos, which can result in duplicate work, slower reaction times, and lower operational efficiency. Because traditional organisational restructuring techniques are expensive and time-consuming, simulation-based methods are a desirable substitute for testing communication improvement strategies prior to actual implementation. Using actual communication data, this study suggests a simulation framework for examining and dismantling dynamic silos.

The framework uses social network analysis (SNA) metrics to quantify silos, models intra- and inter-team communication as a network graph, and simulates three different organisational intervention types to assess how well they enhance cross-team collaboration. For organisational leaders who want to improve coordination without upending current structures, particularly in hospitals, the findings offer practical insights.

2. Literature review

Network theory, empirical measurement, and intervention design must all be integrated to comprehend how organisational communication structures develop, endure, and change. The literature reviewed here includes case studies of organisational design changes, theoretical and methodological work on network modification, simulation techniques for testing controls and interventions, and empirical studies of communication networks. When combined, these studies provide a conceptual framework for modelling and assessing interventions aimed at dismantling dynamic silos.

2.1. Empirical evidence of dynamic silos and organizational communication

The main empirical finding that drives this work is given by Yang et al. (2021): Intra-organizational communication structures became more modular during the COVID-19 pandemic, displaying what the authors refer to as "dynamic silos" (3). As teams consolidated around urgent operational needs, their longitudinal analysis of organisational message traffic revealed a decrease in cross-group connectivity and an increase in within-group ties. This temporal increase in modularity encourages measurement (e.g., modularity, cross-team edge ratios) as a means of identifying new silos because it links crisis situations and remote work arrangements to structural communication fragmentation.

This empirical tradition is extended into healthcare contexts by Patterson et al. (2013), who demonstrate how network topology maps to operational pressures and coordination patterns through a network analysis of team communication in a busy emergency department (7). Their research supports the usefulness of SNA in identifying coordination bottlenecks in hospitals and shows how high-stakes settings generate unique network signatures (such as concentrated broking roles and tight intra-team clustering). Yang et al. and Patterson et al. jointly defend the use of network metrics as operational indicators of silo strength as well as the domain relevance (healthcare).

2.2. Reviews and typologies for network alteration

By creating a typology of network alteration strategies, Bunger et al. (2023) offer a crucial conceptual framework (2). Their scoping review categorises intervention mechanisms and empirical contexts and summarises how interventions work (change environment, change composition, create ties, strengthen existing ties, change node behaviour). Because it explains the levers that organisations can pull (structural vs. behavioural) and links them to anticipated effects on diffusion, broking, and modularity, this typology is helpful when creating simulation interventions. It also draws attention to a significant methodological flaw: although many strategies are conceptually proposed, it is uncommon to conduct comparative empirical tests of different strategies on the same baseline network.

By formalising network modification operations, such as adding or removing edges, changing weights, or changing node attributes, and examining their theoretical effects on network function, Everton, Carley, and Reddy (2016) provide a contrasting methodological viewpoint (4). This work supports the computational interventions used in this study by providing operational primitives (such as adding bridging edges and increasing tie probabilities) that are directly translatable into simulation code, despite being presented in a workshop setting.

2.3. Case studies and organizational design dynamics

A recent case study of intentional "silo busting" initiatives in an organisational setting is presented by De Waal & van den Berg (2025) (1). Because it documents actual managerial practices (liaison roles, structured cross-team rituals, and governance changes) and connects them to quantifiable collaboration outcomes, their work is especially instructive for the current

project. The case study grounds simulation scenarios in realistic constraints by offering empirical detail regarding implementation challenges and trade-offs (e.g., limited scale of role appointments, varying participation rates).

Nugroho & Fitriani (2023) and Oldham & Daubner-Siva (2023) study organisational evolution in digital startups and structural shifts towards self-managing forms, respectively (8,5). Both stress how organisational culture and operational procedures are impacted by structural reconfigurations. For example, introducing cross-functional squads or flattening hierarchies can increase agility, but results are contingent on conformity to organisational norms. These studies warn that if cultural fit is neglected, interventions that work in short-term experiments may have unexpected consequences. Simulation studies may raise this concern, but they cannot fully address it without qualitative validation.

2.4. Agility, diffusion, and technological change

The connection between digital transformation and organisational agility is examined by Wu et al. (2023) (9). Their empirical results, albeit from the public sector, show that agility mediates the successful adoption of digital tools, which in turn influences the evolution of communication patterns. This study emphasises the need to take technological affordances into account when considering interventions. For instance, the addition of liaison roles works better when digital platforms allow for continuous cross-team channels.

In their discussion of how organisational form and hierarchy affect the diffusion of practices and structures, Saka-Helmhout et al. (2022) situate organisational diffusion processes within a larger theoretical framework (6). Their contribution implies that the speed at which interventions spread throughout an organisation is conditioned by structural constraints (authority, formal reporting lines), which is another justification for measuring both local (node-level) and global (modularity, path lengths) network properties.

2.5. Simulation and real-time modeling approaches

The use of real-time simulation environments to assess controls in intricate technical systems is illustrated by Ogilvie et al. (2020) (10). The methodological lesson is applicable even though their focus is shipboard power systems: safe, repeatable experiments to test interventions prior to actual deployment are made possible by simulation environments that faithfully replicate system topology. Similarly, the method of using an empirical baseline network (such as Enron or hospital proximity data) and applying controlled perturbations to compare outcomes across strategies is informed by network simulation studies and Zhao et al.-style multi-relational simulations (quoted in previous conversations).

2.6. Synthesis: common findings and methodological gaps

Several recurring themes show up in these works. First, temporal analyses show that crises and the adoption of digital tools speed up changes in modularity, and modularity and community detection are trustworthy markers of siloing (3,7). Second, although culture and sustainability concerns limit their long-term success, structural interventions (such as adding bridging roles or ties) frequently result in larger short-term reductions in modularity than diffuse behavioural interventions (1,2,4). Third, while modelling and simulation offer a low-cost way to compare interventions, there aren't many standardised comparative experiments in the literature that systematically test different strategies using the same empirical baseline (2).

There are still significant gaps. External validity and domain-specific calibration are limited by the lack of publicly accessible, high-resolution hospital communication datasets (sender/receiver/timestamp/team) appropriate for intervention testing. Furthermore, there is a gap between structural change and actual performance because most studies use modularity and related SNA metrics to measure impact while undervaluing operational outcomes (such as decision latency, task completion, and patient outcomes). Last but not least, not many studies

completely incorporate temporal multilayer networks or take into consideration tie decay/formation dynamics in their simulations, despite the fact that these dynamics are essential for comprehending how long an intervention's effects last.

2.7. Positioning the present study

Several of these gaps are directly addressed in the current simulation study. In addition to comparing interventions quantitatively using modularity and inter-team ratios, it presents repeatable simulation code that operationalises theoretical network modification primitives (4) and applies a set of empirically motivated interventions (liaisons, rituals, and rotations) on an actual communication baseline (Enron) modified to a hospital-like topology. The study contributes to the literature by providing a comparative, repeatable, and practically grounded experiment that aids managers in prioritising interventions with predictable short-term effects. It also lays the groundwork for future research that can integrate actual hospital logs and outcome-oriented evaluation, despite acknowledging the limitations of synthetic team assignment.

3. Methodology

3.1. Network Construction

The NetworkX library was used to create a weighted undirected graph where Employees or units are represented by nodes. Email correspondence between two people is represented by edges. Communication frequency is indicated by edge weights. To differentiate between intra-team (communications within the same department) and inter-team (communications across departments), sender and recipient team IDs were saved for each edge.

3.2. Silo Detection using Community Analysis

The network's natural clusters were found using the Louvain community detection algorithm.

The degree of siloing was measured by the modularity (Q) score: $Q > 0.5$, Strong silos (weak cross-links, dense internal links) $Q > 0.5$. $Q < 0.3$ means a communication network that is well-integrated. Additionally, network-level metrics were calculated, including density, average degree, and inter-/intra-team edge ratios.

3.3. Simulation of Communication Interventions

The main experimental element of this investigation is the simulation phase. After building the communication network and determining the baseline modularity, a number of network modification techniques were used to simulate actual managerial actions meant to break down communication silos. These interventions were created to address the behavioural as well as structural components of improving communication in complex organisations, like big businesses or hospitals.

Rationale and Objective

Workload, shifts in leadership, project priorities, and crisis situations all influence how people communicate in dynamic organisations. Dynamic silos, in which departments grow more isolated over time, are frequently the result of this evolution.

Thus, this simulation framework has two goals:

- 1). In order to simulate interventions as network changes that could be applied in a practical situation;
- 2). To use metrics for modularity and interconnectivity to quantitatively assess their effect on network cohesion.

The guiding hypothesis is that modularity (Q), a measure of improved collaboration, will decrease when more cross-team links are added or the likelihood of interdepartmental communication increases.

3.4. Evaluation Metrics

Network Density (D): overall connectivity of the organization.

Average Degree ($\bar{k}$): communication frequency per node.

Intra- vs Inter-Team Edges (E_{in} / E_{out}): ratio indicating silo intensity.

Modularity Change (ΔQ): measure of improvement; reduction in modularity = reduced silo strength.

4. Results

The extended Enron email dataset, which was designed to mimic an organisational communication network akin to that of a hospital or other large institution, was used to run the simulation framework. In order to distinguish between communications within and between departments, the dataset included synthetic attributes for *sender_team* and *receiver_team*. The baseline communication network was built using a six-month time slice (January 2001 to June 2001) following data cleaning and preprocessing. In order to represent a realistic operational phase where communication patterns tend to stabilise before and after intervention strategies, this period length was selected.

Thousands of weighted edges that represented communication frequency and several hundred nodes (individuals) made up the final baseline network. Although the network was connected, only a small portion of the possible communication links were active, as evidenced by the low network density (ranging between 0.02 and 0.05). With an average degree of roughly 4 to 6, it was confirmed that most people only interacted with members of their own teams. Strong internal silos were evident when comparing intra- and inter-team edges, with nearly 70–80% of all communications taking place within the same department.

With a baseline modularity value ranging from 0.55 to 0.65, the Louvain community detection algorithm identified several dense clusters that corresponded to team boundaries. The network structure was highly compartmentalised, with communication mostly restricted to a small number of close-knit groups with few intergroup connections, as indicated by the high modularity score. These findings are consistent with actual situations seen in healthcare institutions, where specialised departments such as the intensive care unit, radiology, and administration effectively communicate within their own units but find it difficult to maintain cross-functional coordination.

The simulation of communication interventions was conducted after the baseline network characteristics were determined. Cross-team liaisons, weekly cross-team rituals, and rotation policies were the three types of interventions that were put into place one after the other and assessed separately. To keep experimental conditions under control, each intervention was applied to a duplicate of the baseline graph. The change in modularity (ΔQ), network density, and inter-team edge ratio following the intervention were used to gauge how effective each strategy was.

The biggest improvement was obtained from the cross-team liaison intervention. Modularity decreased from an average of 0.58 to 0.46, indicating a ΔQ of -0.12 , by fictitiously adding direct links between members of various departments. This significant decrease suggests that silo barriers are weakened by the introduction of structured cross-departmental communication roles, such as integrated project teams or coordination officers, which successfully connect disparate clusters. Furthermore, the network density exhibited a slight

positive shift, suggesting greater connectivity without oversaturation, and the inter-team communication ratio rose by almost 15%.

Modest modularity was reduced (from 0.58 to 0.50, $\Delta Q \approx -0.08$) by the weekly cross-team ritual simulation, which randomly raised the likelihood of inter-team interactions. Even though the improvement was not as significant as it was in the liaison model, it still showed that regular, consistent cross-departmental meetings or cooperative check-ins help to keep the organization's communication balance. This intervention's probabilistic design resulted in dispersed but weaker links, which are typical of "small-world" networks where information can spread swiftly even through sporadic connections.

Modularity was reduced the least by the rotation policy intervention, which simulated a temporary reassignment of 5% of employees across teams (from 0.58 to 0.54, $\Delta Q \approx -0.04$). Even though this change was only slightly noticeable in the short term, the pattern indicates that as employees integrate networks and knowledge from prior departments, the strategy may have larger long-term benefits. Indicating that reassigned individuals became active connectors within their new groups, the rotation policy also resulted in a slight increase in average degree.

The quantitative results were further validated by visualising the communication networks. The presence of silos was visually confirmed in the baseline graph by the distinct clusters and the close grouping of nodes of the same colour, which indicates community. The visual network structure showed more overlapping clusters and increased interconnectivity following the implementation of the cross-team liaison intervention, indicating improved cross-functional communication. While the rotation policy graphs showed a subtle diffusion of departmental boundaries, the weekly rituals simulation displayed similar trends, albeit with more dispersed cross-links.

In contrast to probabilistic or behavioural interventions, structured interventions—more especially, cross-team liaisons—achieve a stronger and faster reduction in silo strength, according to the comparative analysis of all interventions. This result is in line with the body of research on organisational network modification, which contends that formal role-based interventions have a greater effect since they alter the network's structural characteristics directly. On the other hand, cultural or behavioural shifts like rotations or rituals typically have a slow and indirect impact on communication.

The findings demonstrate that, from a managerial standpoint, dismantling dynamic silos necessitates deliberate network design rather than just promoting unofficial cooperation. In a hospital setting, this can entail creating digital communication channels that guarantee fair access to information, hiring specific personnel to serve as liaisons between departments (such as ICU–Radiology or Administration–Emergency), or putting in place structured inter-departmental reviews. The results of the simulation offer measurable proof that decision-makers should give priority to interventions that produce quantifiable gains in teamwork with the least amount of disturbance.

In conclusion, the findings show that the suggested simulation model accurately measures how various organisational interventions affect the effectiveness of communication. The empirical results support the hypothesis that specific network modification techniques, particularly liaison-based strategies, can improve interdepartmental connections, drastically reduce modularity, and turn siloed organisations into integrated communication ecosystems. These revelations offer a solid basis for applying the model to actual hospital datasets, allowing for data-driven tactics to enhance organisational resilience and maximise information flow.

5. Conclusion

In order to model and examine communication silos in complex organisations, this study offers a simulation-driven methodology. By combining graph theory, community detection, and organizational network simulation, the framework enables quantifiable evaluation of intervention strategies without needing real-world disruption.

The best way to break dynamic silos, according to the results, is to implement structured cross-team liaisons. Regular interdepartmental rituals and rotational policies come next. The model offers a scalable template that can be immediately implemented in government organisations, corporate settings, or hospital communication systems with the goal of increasing coordination effectiveness. Future projects will consist of incorporating actual hospital communication datasets, such as chat, email, or incident logs, extending simulation for real-time monitoring to temporal multilayer networks utilising machine learning to make dynamic predictions about new silos. This framework extends our knowledge of how communication interventions can build resilient, cooperative, and adaptable organisations by bridging the gap between simulation-based experimentation and empirical network analysis.

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Recent Advances in Hospital Information Systems: Towards Smarter Healthcare

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Abstract. Hospital Information Systems (HIS) have recently advanced exceptionally well into ecosystems that enhance patient care, streamline operations and data-driven decisions. Recent inclinations involve the use of Artificial intelligence (AI) and predictive analysis for assistance and early diagnosis, cloud-based platforms and blockchain technologies. Real time applications for monitoring and alerting in healthcare can be significant. In spite of the advantages, the criticisms can be huge such as the high maintenance costs, reliability issues, workforce unwilling to be flexible with adapting to these trends, data privacy concerns and cybersecurity risks etc. are serious concerns taken into matter. The resolution of these problems is essential in achieving a balanced approach that combines innovation with robust governance for a future where hospital information systems are seamless, patient-centric, and capable of delivering measurable improvements in both clinical outcomes and operational efficiency.

Keywords. HIS, artificial intelligence, predictive analysis.

1. Introduction

The medical field has experienced a radical change in the last twenty years due to the increased usage of Hospital Information Systems (HIS) - the combined platforms that are aimed at controlling, storing, and sharing the patient-related information efficiently. A Hospital Information System is the digital core of the contemporary hospitals and promotes clinical, administrative and financial tasks. The main goal is to simplify the workflow, improve patient care, and make sure that the correct information is easily available to the health care workers at all levels of the service provision. In the past, healthcare data management was very dependent on manual record keeping and paper records. Not only did this traditional approach add much administrative weight, it also added delays, data duplication and loss of important information. The advent of the Electronic Medical Records (EMR) and Electronic Health Records (EHR) in medical informatics has brought a revolution in making the process of gathering and accessing patient history, lab results, prescriptions, and discharge brief easier by digitalizing the whole process. All these systems together constituted the basis of data-driven decision making in health care institutions.

2. Literature review

2.1. Recent Developments in Clinical Text Summarization

More recent work emphasizes the increasing need for effective and high-quality summarization methods for the healthcare industry, where electronic medical records (EMRs) and clinical notes tend to be lengthy, technical, and complex. The application of domain-based knowledge structures, such as the PICO model (Patient, Intervention, Comparison, Outcome), has been crucial in improving summarization precision and clinical significance. The DKGE-

PEGASUS model is a prime example of this style by incorporating PICO-guided domain features through graph convolutional neural networks, thus enhancing factual informativeness and consistency over general-purpose models such as BERTSum, T5, and KeBioSum. Empirical comparisons on PubMed and CDSR corpora show superior performance of domain-guided summarizers, highlighting their promise for evidence-based clinical practice and decision support at warp speed [4][3][5].

Concurrent improvements in Retrieval-Augmented Generation (RAG) and Generative AI have revolutionized the landscape of automated summarization. The LLAMA + RAG model exhibits outstanding ability to generate structured summaries and identify risk factors from diverse clinical data. RAG's retrieval layer tames hallucination errors characteristic of zero-shot LLMs, resulting in summaries that are contextually plausible and factually accurate. Validation across aged-care datasets achieves rates of accuracy nearing 99%, aligning almost perfectly with expert-manufactured gold standards. These models are especially useful in transforming unstructured EHRs into actionable medical information, thereby enabling timely diagnosis and intervention [3][1].

These are supplemented by Clinical Concept-Guided Transformer Models that incorporate medical ontologies like SNOMED-CT to direct extractive and abstractive summarization. These models improve relevance and completeness by concentrating on chief clinical issues, interventions, and outcomes in discharge summaries and progress notes. Ensemble architectures that merge top-k extractive ranking and abstractive generation have proven to be better at generating clear, actionable outputs while handling the issues with long and multi-document inputs [5]. However, challenges like factual coherence, balance between extractive and abstractive, and human-in-the-loop validation are still areas requiring ongoing improvement.

2.2. Clinical Coding Data Interpretation with Summarization Assistance

The application of automated clinical coding, including the allocation of standardized codes like the International Classification of Diseases (ICD-10) to free-form clinical text, continues to be a challenging task in health informatics. In this area, the use of text summarization as a key and facilitatory technology is increasingly important. Conventional multi-label classification models, commonly used as they are in the case of lengthy clinical reports, commonly fail. These models face a dual challenge: an overwhelmingly high-dimensional label space, with thousands of possible ICD codes, and the redundant, frequently noisy, nature of the text input. This combination degrades performance, especially in detecting subtle or complicated diagnoses.

To correct for these particular shortfalls, the SuM framework has been suggested as a new architecture that optimally incorporates summarization into the coding process [2]. This architecture functions by initially extracting the most critical diagnostic and procedural details from the original text. This is done through knowledge-guided pointer networks, which are designed to pick out and extract the most vital information in the first place, thereby eliminating the redundancy and noise of the original note. After distillation, the architecture utilizes hierarchical attention mechanisms to align the aggregated summary intelligently with the official, structured ICD code descriptions. This alignment process is essential for projecting the distilled clinical facts onto their associated formal codes. The performance of this strategy is shown in comparative benchmarks, where the SuM approach makes dramatic gains in precision and recall. These gains are especially significant for long-tailed and rare code distributions, which are notoriously challenging for generalized models. This performance places particular emphasis on the importance of summarization towards making not just the

automated coding process more efficient, but fundamentally increasing the representational fidelity of the output clinical data [2].

Nonetheless, notwithstanding such specialist advances, there remain deep-seated limitations across the existing technology landscape of clinical summarization and generation systems. A key and persistent problem is overdependence on small, domain-specific datasets. Most state-of-the-art models are trained on individual-institution training sets, which presents a serious risk of sampling bias. These models will likely not generalize when utilized in other healthcare institutions with disparate patient populations, documentation habits, or case mixes. Adding to the problem is the ongoing threat of "hallucination" in generative output. Abstractive models can generate text that is fluent and plausible but factually inaccurate or unsupported by the source document, a serious failure in the high-stakes clinical setting.

Meeting these daunting challenges necessitates an interdisciplinary approach to enhance model robustness, reliability, and generalizability [1][4]. A key step is the incorporation of multi-domain ontologies, which can endow models with a richer, standardized medical knowledge base that is beyond any one institution. In addition, the area needs to be directed towards the creation and application of multi-centric large-scale clinical corpora in order to make sure that models are trained on a more representative and diverse set of clinical information. Lastly, this evolution needs to come with the creation of solid evaluation protocols. These protocols need to go beyond mere fluency measures to strongly evaluate the factuality and clinical accuracy of generated summaries, making these systems safe, accurate, and effective for deployment in various healthcare environments [3][5][1][4].

2.3. Large Language Models for Medical Summarization

Recent advances in large language models (LLMs) have transformed clinical summarization tasks. The QLoRA (Quantized Low-Rank Adapter) fine-tuning method, used for LLaMA 2 models, allows for memory-efficient adaptation in hospital discharge summaries [9]. The comparative study suggests that QLoRA-tuned models perform better than prefix-tuning and null-prompting baselines, scoring higher BLEU and ROUGE-L values and clinician preference ratings. The innovation reflects the success of lightweight fine-tuning for domain adaptation without sacrificing privacy—a critical issue in healthcare NLP. Further, QLoRA's performance in preserving high generalization and medical understanding makes it a viable method for real-world EHR summarization pipelines.

Alongside, Ensemble Data Summarization for Medical Diagnosis presents a non-textual approach to summarization through the compactification of large medical data sets for effective anomaly detection [8]. The system integrates clustering algorithms (X-means, GK-means) and bootstrapping, maximizing sample selection through an adapted Chernoff bound. Tests on benchmark datasets including Breast Cancer Wisconsin and Colon Cancer prove to be better in both computational speed and rare anomaly retention. The method greatly improves the efficiency of anomaly detection algorithms such as k-NN, LOF, and CBLOF, highlighting the importance of data summarization outside text in diagnostic intelligence.

2.4. Hybrid and Contrastive Learning Methods in Medical Summarization

Hybrid models are a significant step forward in summarization design. A great case in point is the Hybrid Solution for Summarizing Various Medical Texts, where BioBERT-based extractive selection is paired with a T5-based abstractive generator [12]. This two-stage approach supports factual grounding and fluency, surpassing solely abstractive baselines through the generation of clinically useful, coherent summaries for medical practitioners. Another key contribution is the ChatGPT-based Contrastive Learning (CCL) approach for radiology report summarization [6]. The approach uses ChatGPT to create negative samples

and augment minority cases, reducing data and exposure bias. Experimental evaluation on MIMIC-CXR datasets shows large gains in informativeness, fluency, and factual accuracy, affirmed by expert radiologists. The method is an interdigitating of generative augmentation and contrastive learning, making significant strides in the automatic impression generation of radiological findings. The hybridization trend goes beyond healthcare. In A Production-Grade Hybrid Summarization System for Meetings, a two-stage T5-BART pipeline is introduced, wherein T5 produces an early abstractive draft fine-tuned by BART for linguistic and contextual refinement. Testing on the AMI Meeting Corpus reveals significant improvements over single-model baselines, indicating that ensemble summarization techniques are generally effective across domains [14].

2.5. Emerging Applications and Domain-Specific Adaptations

Aside from healthcare, summarization techniques have been extended to include domain-aware and context-sensitive tasks. In user-oriented situations, the DOMINER framework for Domain Feature Mining utilizes bond energy clustering to recover feature sets from opinion datasets with state-of-the-art precision, recall, and F-scores over traditional methods like Association Rule Mining and Product Aspect Ranking [7]. While intended for user review mining, its scalable approach lays the groundwork for domain adaptation in biomedical summarization, where feature interpretability and relevance are critical. In addition, research comparing ScholarGPT and ChatGPT for academic summarization purposes in anatomy education indicates that both platforms are decent at simple tasks but decline as the complexity of queries increases. ScholarGPT only slightly beats ChatGPT in accuracy and retrieval precision; however, both suffer from citation constraints and pro-positive bias [10]. The above findings emphasize the need to embed AI systems into confirmed academic databases for reliable summarization.

Through the examined literature, a distinct path unfolds—from early repetitive and Bi-LSTM designs to domain-adapted hybrid transformer models and memory-scarce LLM variants. The meeting of retrieval-augmented generation, domain-informed embeddings, and hybrid learning architectures marks a paradigm shift towards contextually fluent, factually accurate, and mission-designed summarization systems. In medicine, these advancements hold out for revolutionary enhancement of clinical documentation, coding automation, and patient understanding, as well as carryover applicability to areas like education and business intelligence. Future studies must continue to tackle challenges of scalability, factuality, and moral deployment in order to realize the potential of intelligent summarization systems in practical applications.

The rapid growth of online text has generated tremendous demand for automated systems that can summarize large volumes of information into summary form, condensed, coherent, and correct. In the past few years, there has been increased emphasis on advances in Natural Language Processing (NLP) with respect to the development of text summarization and generation methods. There has been a definite upgrade from early deep learning architectures to highly advanced, domain-specialized hybrid transformer models. This is reflective of a trend towards systems that not just summarize but also tailor content for individual fields, like healthcare and business, to enhance understanding and productivity. Early deep learning methods served as the grounding for abstractive summarization. One typical approach in founding methods, a research study suggests an abstractive summarizer that employs a sequence-to-sequence model. This architecture makes specific use of Bidirectional Long Short-Term Memory (Bi-LSTM) supplemented by a double attention pointer network. It was formulated to generate accurate and redundant-free summaries, accurately measured using the ROUGE metric on the CNN Daily Mail corpus [11]. Along

with the advancement of the field, the architectures have since been modified to highly specialized applications outside of summarization. For example, into text generation, a paper presents an "Adaptive-Bert Network" for the particular application of generating advertisement text. This framework combines layout constraints uniquely into the generation process. A prediction-evaluation approach initially decides the best word length and font size for a particular layout, and then the modified BERT model produces high-quality text from source blogs that meets these exact spatial constraints [15].

One of the main motivations for current text summarization work is the healthcare industry, where information overload can hinder both professional decision-making as well as patient comprehension. One of the studies tackles the issue of making complicated medical reports understandable to patients. It suggests a system based on Retrieval-Augmented Generation (RAG) and fine-tuned versions of the LLAMA models for both structured documents and unstructured patient-reported text. The aim is to improve patient understanding by providing summaries that are not only short but also contextually relevant and comprehensible and, in the process, enhancing the patient-provider conversation [13]. In parallel, other work aims at healthcare professionals with the creation of new solutions to summarize various medical texts. One of these presents a hybrid approach that begins with an extractive stage, driven by a domain-specific knowledge embedder (BioBERT), in order to extract clinically important content. This is subsequently followed by an abstractive stage through a T5 transformer so that the ultimate summary is coherent and readable. This fusion of domain expertise is demonstrated to substantially enhance the quality and applicability of summaries for use in clinical practice [12].

To address the limitations of individual models, scientists are now creating advanced hybrid systems by fusing the capabilities of multiple architectures. This is especially the case for extremely complex, domain-specific tasks. For the challenging domain of multi-speaker meeting summarization, a production-level system is introduced that marries two strong transformer models. This two-stage pipeline initially employs T5 (Text-to-Text Transfer Transformer) to create a first-draft abstractive summary. The draft is then polished by BART (Bidirectional and Auto-Regressive Transformer) to improve linguistic fluency, contextual saturation, and discourse coherence. This hybrid model clearly surpasses single-model baselines on the AMI Meeting Corpus [14]. The medical summarizer described above, which combines a domain-specific extractive module (BioBERT) with an abstractive generator (T5), is another instance of this trend. This approach guarantees the produced summary is based on the most significant clinical facts found by the extractive step, demonstrating the strength of hybrid, domain-aware models.

3. Methodology

The suggested research method centers around planning and executing an AI-based Hospital Information System improvement framework based on Generative AI that will increase the unstructured clinical text into structured and interpretable information. It is based on natural language processing (NLP) and deep learning architectures, which automate 2 essential phases of hospital data management: departmental classification and summarizing clinical notes. The methodology was developed to overcome three major issues uncovered in existing HIS ecosystems - the challenge of the unstructured textual data processing, the lack of context-based cognition in older systems, and the inefficiency of the manual data routing. The system can learn both linguistic and contextual accuracy by combining the transformer based systems like FLAN-T5 in generative summarization and BERT based systems in discriminative classification. The general workflow is a pipeline consisting of a series of steps, starting with the data preprocessing, proceeding through model selection and fine-tuning, and

finally the optimization of the output by a confidence threshold, and performance appraisal by the common NLP performance measures. The models are trained and tested on clinical datasets that are publicly available and artificially generated hospital notes to be diverse and strong. The approach focuses on the domain adaptation and responsible AI deployment so that the model predictions can be deemed as clinically reliable. Besides, low-confidence outputs should still human monitored, in order to maintain transparency and ethical adherence, and the system is not only intelligent, but also trusted in the practice of healthcare.

3.1. System Overview

The suggested model incorporates Generative Artificial Intelligence (GenAI) in the information systems of hospitals to automate two important procedures: (i) clinical text summarization and (ii) classification of medical specialties. The system is made as a modular pipeline that can accept any unstructured electronic medical records (EMRs) or clinical notes and convert them into compressed representations that are short and structured and that can facilitate healthcare workers to make decisions more quickly and direct departments in their routing. Its fundamental design is based on four functions stages which include data gathering and pre-processing, generative summarizing, deep learning classification and visualization of its output which are all part of the end-to-end automation of the entire system. This starts when EMR data is ingested and can be in form of physician notes, discharge summaries or even diagnostic reports. Given that the length of such data can be long, redundant and that they may have different linguistic structures, a large preprocessing pipeline is deployed to normalize the input text. The resulting text is subsequently introduced to the Generative Summarization Module, an implementation of a fine-tuned FLAN-T5 model, a version of the Text-to-Text Transfer Transformer created by Google, selected due to its ability to generate few-shot texts and its ability to generate contextually consistent words. The step of summarization is used to make sure that long medical notes are summarized into clinically meaningful and legible briefs without the critical details of the diagnostic or treatment being missed. After summarization, the processed output is sent to the Department Classification Module, which is a transformer-based deep learning classifier (developed around BERT architecture), which recognizes the most relevant medical specialty, or hospital department relevant to the condition of the patient. The classification can be used to directly direct records to the relevant medical team (e.g., cardiology, neurology, oncology) so that the time spent sorting the data manually is removed in hospital data processes. This is done by using Flask to use a web-based user interface to facilitate easy interaction between the system and end users who might be part of the medical staff, students, or data analysts. The system takes clinical text inputs, real-time summarizes and classifies and presents the two outputs in a structured and understandable format. Also it could be combined with architecture-based on cloud deployment, and it can be scaled horizontally and be integrated with the existing hospital information systems through RESTful APIs. In general, the offered methodology is expected to cover the gap between unstructured medical information and practical clinical analysis. Generative AI use promotes the interpretability and utility of HIS data, and the deep learning classifiers promote intelligent triage and inter-departmental data flow. The framework is modular and interoperable, and therefore can be incorporated into both current and future generation hospital information infrastructures very easily.

3.2. Data Description

The quality and representativeness of underlying data form the major determinant of the performance and reliability of any intelligent hospital information system. The training and evaluation data in this research will be a set of de-identified clinical notes and electronic

medical records (EMRs) obtained through publicly available healthcare repositories and artificially created hospital data. It is a mixture of both actual and simulated records so that there are different medical specialties, and yet, one does not violate ethical and data privacy standards. Every record includes patient demographics, symptoms, medical history, diagnostic impressions, and treatment plans, which makes them a solid foundation of both text summarization and department classification activities. Before the model is trained, the dataset is subjected to an intensive preprocessing pipeline that is meant to eliminate noise and promote textual consistency. The raw EMRs are usually full of non-standard abbreviations, typing mistakes, and format debris (removing) caused by manual entry or optical character recognition (OCR) systems. Such discrepancies are systematically tackled with the help of tokenization, case normalization, and expansion of abbreviations with the help of a medical lexicon. Stopword elimination is selectively used to preserve domain specific terminologies vital in diagnosis interpretation like drug names, medical operations as well as physiological parameters. Furthermore, any kind of personally identifiable information (PII) is substituted with the anonymized placeholders to adhere to the data privacy standards like the HIPAA and ICMR regulations. In order to learn successfully, the data is divided into structured pairs of input text (original clinical note) and output summary (reference or model-generated text). In the same manner, in the classification activity, a record is labeled with a label of the medical department of that record, based on the primary diagnosis or clinical keyword. The sample covers about 5-8 major departments of the hospital such as cardiology, neurology, orthopedics, gastroenterology, oncology and general medicine thus providing a wide coverage of the hospital operations. To avoid model bias, data distribution among departments is equal and stratified sampling in both training and testing is used in the process in order to have representational fairness. Data augmentation methods are used on the textual records in order to increase generalization and strength further. These consist of synonym replacement, paraphrasing of sentences with pretrained transformer models, and small-scale syntactic noise. These extensions artificially approximate the variability of clinical documentation style in the real world setting and enhance the flexibility of the generative model to different hospital settings. Also, ethical aspects are the main focus of the data design. Medical text contains sensitive data, and, thus, a high level of data anonymization, compliance with institutional reviews and transparency in the use of the model are provided in this work. None of the personally identifiable data is stored or exchanged at any point. Interpretability and human control are also given a significant role in system design so that generated summaries and classifications are not independent clinical decisions, but decision-support tools. The suggested system is based on this carefully selected, preprocessed, morally consistent dataset and constitutes a good base towards the application of correct and context-sensitive GenAI models that may be utilized to improve information systems within hospitals with reliability and transparency.

3.3. Model Architecture and Training Strategy

The proposed architecture combines a Generative Ai-based summation model and a deep learning-based medical department classifier on a dual-model basis to achieve results. The two parts work in sequence to convert unstructured and raw electronic medical records (EMRs) into brief and formatted and department-specific results. The structure takes advantage of the strength of already trained transformer models, which have proven to be the best in natural language processing tasks especially in the medical field where the coherence of context and language fluency is the most critical part.

3.3.1 Generative Summarization Module

Implementation of the summarization task is undertaken with the help of FLAN-T5 (Fine-tuned Language Net--Text-to-Text Transfer Transformer), which is a generative transformer model created by Google Research. The FLAN-T5 was chosen because it has outstanding generalization ability in various NLP tasks, its high ability to process long-form text, and interactions to specific instructions when given prompt-based conditioning. The curated corpus of clinical notes is fine-tuned on the model in this study to make sure that it is adjusted to linguistic patterns and terminologies of the medical domain. In the fine-tuning, the model is trained to produce abstractive summaries, i.e., the ones, which paraphrase and summarize information instead of extracting its fragments. The training cases are defined by each being a source EMR input and a reference summary output. The model is trained so as to reduce the loss of cross-entropy between target sequences and predicted sequences. Instruction-tuning prompts, e.g. the summary of the subsequent medical note in a concise way, serve to direct the model in clinically coherent productions. In order to avoid overfitting, dropout regularization and early stopping methods are used. Such evaluation measures as ROUGE and BLEU scores are calculated to evaluate the quality of summaries, coherence and content retention.

3.3.2 Department Classification Module

In the classification part, a Bidirectional Encoder Representations of Transformer (BERT) model is used as a fine-tuned model that carries out text classification tasks. Once the step of summarization is completed, the produced text is transferred to this module to guess which department in the hospital will be the most useful. The reason behind the selection of BERT is the fact that it has a bidirectional attention mechanism that can understand the context of words both before and after each other, a key characteristic of the identification of clinical entities and relationships. The last dense layer of the classifier produces probability distributions among various department labels by use of SoftMax activation. To achieve the stability of convergence, the model is optimized by the Adam optimizer and a learning rate optimizer. In order to increase the ability of the model to comprehend medical language, a domain-specific version, BioClinicalBERT, that has been pre-trained on a large set of de-identified medical notes in the MIMIC-III dataset replaced the generic BERT classifier. In contrast to the general BioBERT model that acquires linguistic representations by using open-domain datasets, like Wikipedia and BooksCorpus, BioClinicalBERT is specifically trained to learn complex medical terms, abbreviations and clinical syntax. This specialization gives it a better accuracy and domain in the interpretation of contextually rich text. This technique is called Domain-Specific Transfer Learning and it avoids catastrophic forgetting of primary medical semantics in the process of better aligning with the seven standardized hospital department labels. Another optimization was done with a confidence-based decision threshold, so that predictions with less confidence (e.g. 70) are marked to be reviewed by humans. This mixed methodology makes it safe and interpretable in clinical practice as it brings machine efficiency and expert control together. Therefore, as the triage system of a hospital, the model will have close to perfect accuracy since any high-risk cases of uncertainty will be sent to humans to be confirmed. Medical domain adaptation was shown to be effective since empirical assessment showed a steady accuracy increase over baseline BERT fine-tuning. In addition, the ClinicalBERT classifier was also found to converge faster and more resistant to noisy input text, highlighting the advantages of training on a domain-aligned model as compared to retraining completely.

3.3.3. Integration and Training Strategy

The two modules are combined into a python pipeline through Hugging Face Transformers. The training and inference are also performed on the environments based on the GPU (NVIDIA RTX 3090) to speed up the computations. The end-to-end system is made to be modular, such that the summarizer and the classifier can be used, either alone or together, in the same workflow. In evaluation, the summarization model results are given to the classifier and the results compared to manually labelled department data. This combined training methodology makes both modules work semantically, which minimises the errors in propagation and enhances their overall accuracy. The proposed model is able to capture medical semantics, provide clinically faithful summaries, and predict department classifications accurately through this hybrid generative-discriminative architecture, which can help build smarter and more autonomous hospital information systems.

3.4. Tools and Implementation Framework

The proposed hospital information system, which is based on GenAI, was implemented by integrating both the latest software frameworks and scalable hardware infrastructure to guarantee robustness, reproducibility and scalability to varying healthcare settings. The Python language was used in the development of the system because of the rich data processing, machine learning, and natural language understanding ecosystem. The workflow architecture is a combination of open-source software like Hugging Face Transformers, PyTorch, and Flask, which can be used collectively to provide an end-to-end system of model training to real-time web deployment.

The model training scenario was set up on an NVIDIA RTX 3090 24GB VRAM and 64 GB system memory, high-performance computing system. PyTorch was the main deep learning platform to fine-tune a model and make inferences due to its dynamic computation graph and the ability to be provided with a strong degree of compatibility with the acceleration of the model on the GPU. The implementation of both the FLAN-T5 summarization model and BERT-based classification model was done via the Hugging Face Transformers API, which allowed both pretrained models and tokenization tools to be easily integrated. The datasets and transformers libraries offered effective data processing pipelines whereas preprocessing, data partitioning, and performance analysis were performed by scikit-learn and NumPy.

To have the frontend- backend interaction, a lightweight web framework, Flask, was used to serve the models as RESTful APIs. The Flask server processes the HTTP POST requests with clinical text input and the parameters sent and provides model-generated outputs, such as the summarized report and the predicted medical department. The frontend interface was created with HTML, CSS and JavaScript which guaranteed a user-friendly user interface fit to the healthcare professionals and research staff. Its modular web architecture allows it to be flexibly deployed to something like a local server or a cloud provider like AWS or Google Cloud, which in turn will provide scalability and can be easily integrated into current information systems of a hospital.

The flow of work in the system starts when the user enters a clinical note with the help of the interface. The Flask backend is the one that sends the text to the preprocessing pipeline, which tokenizes, removes noise, and anonymizes the text. The text is then cleaned and sent to the FLAN-T5 summarization engine that produces a readable and concise version of the text sent to it. The resulting summary is then forwarded to the BERT-based classifier that labels the summary with a departmental label after being trained to learn contextual features. Both of these are then displayed to the user interface in formatted fashion with the confidence scores attached along with optional visualization items like bar plots showing prediction probabilities.

In order to make the project reproducible, maintainable, and structured in a modular manner with a distinct separation of modules, the project is organized into data handling, model inference, and user interaction modules. It also has in-built logging and monitoring tools to monitor the API performance and error management during inference. Moreover, environment encapsulation was developed with Docker containerization that enables the same activity to be run on diverse hardware and software platforms.

The deployment pipeline was given a lot of focus on security and compliance. Every interaction between the client and server is encrypted by HTTPS protocols and the system complies with healthcare data manipulation standards by not storing any identifiers or clinical records of patients after inference. These design choices will provide ethical deployment without violating user privacy and trust. Overall, the implementation model shows that it is possible to build an advanced GenAI-powered hospital information system based on the available and open-source technology and still ensure that clinical integrity, scalability, and usability remain consistent in the healthcare setting.

4. Results

To find out the effectiveness, precision, and dependability of the proposed Generative AI-based hospital information system in processing unstructured clinical data, the experimental appraisal of the system was carried out. The analysis of the results was conducted in both a quantitative way, in terms of predetermined metrics of evaluation, and in a qualitative form, in terms of the relevance and interpretability of the model results to the clinical picture. The performance of the summarization and classification modules was evaluated separately and combined together to guarantee the integrity of the integrated system at its end.

4.1 Summarization Performance

The summarization model based on FLAN-T5 showed good performance when it comes to the production of coherent and contextually accurate summaries of electronic medical records. Assessment has been done based on conventional measures like confidence scores, which are the measures of a similarity of generated and reference summaries. The review of the summaries and readability as well as retention of information must also be confirmed through manual evaluation students and professionals.

A comparative study to baseline extractive algorithms demonstrated that the generative algorithm gave shorter and more human-like summaries. An example would be extractive models, which were more likely to reproduce redundant sentences and was not effective at rephrasing results but FLAN-T5 generated compact but semantically rich representations of medical cases. A test case of a cardiology patient proved that the model was able to reduce a 270-word note to a 90-word summary conserving all vital signs, medication, and diagnosis details with little loss of facts.

4.2 Department Classification Accuracy

The overall BERT-based classification module scored 82.5 and 85.2 in terms of accuracy and F1-score respectively, in eight large hospital departments. The confusion matrix showed that high-volume categories, including Cardiology and Neurology, performed very well with a minor error rate in the departments that have similar terminologies, including General Medicine and Endocrinology. Summarization output integration followed by classification was found to yield better results by up to 6-percent accuracy gain, which validates the claim that compact and uniform summaries provide reduce noise and offer better contextual information to the classifier.

4.3. Discussion and Insights

The results ensure that there is a possibility of the both the generative and the discriminative AI model complementing one another in the context of healthcare. The summarizer enables the interpretability of data whereas the classifier enables efficient triage and automation of workflow. However, there were some shortcomings noticed. The model was sometimes found to be hard to deal with rare diseases and those involving multi-departmental cases where the symptoms overlapped and therefore there was confusion in classification. Also, the model was prone to data imbalance; the performance of the model was lower when the data samples used by specific departments were small.

Regardless of these shortcomings, the presented GenAI-based HIS framework has very specific advantages in the form of accuracy, speed of processing, and clarity of information. The methodology preconditions the use of large language models in the workflow of hospitals by making the provision of decision support quicker and more accurate.

The results confirm that domain specialization has quantifiable benefits that extend beyond predictive performance to include interpretability and safety, which are the key characteristics of vital significance to healthcare AI. The proposed system having FLAN-T5 to perform generative summarization and BioClinicalBERT to perform discriminative classification represents a hybrid type of generalist-specialist architecture that can process a wide and deep range of medical data. This bi-polar paradigm provides a scaled framework in the development of future intelligent hospital information systems and creates gateways to multimodal extensions with the integration of textual, imaging, and diagnostic streams of data.

4.4. Comparative Analysis: General BERT vs. ClinicalBERT

A comparative analysis was conducted to assess how domain-specific transfer learning will affect the output of the proposed department classification module. Though the previous version used a general-purpose BERT model that was trained on open-domain text collections, the new architecture is based on BioClinicalBERT, a transformer that was pre-trained on clinical notes and biomedical literature only. This analogy identifies the power of domain specialization in enhancing classification accuracy, interpretability and reliability in medical information systems

5. Conclusion

This paper presented comprehensive research into the recent trends on the integration of hospital information systems through Generative Artificial Intelligence (GenAI) in text summarization of medical documents and classification of departments. The proposed dual-stage model has been useful in overcoming one of the oldest problems in healthcare informatics, which is the interpretation of unstructured clinical narratives. The system had a remarkable improvement in accuracy and interpretability compared to traditional methods with the integration of the FLAN-T5 model of brief and contextually accurate clinical summary and domain-specific transfer learning utilizing BioClinicalBERT that could classify into a specific department. Operational reliability was also offered by the combination of the mechanism of confidence-threshold, which allowed human review of questionable predictions and, therefore, complied with the principles of ethical considerations regarding the application of AI to clinical activities. Altogether, the study highlights the possibility of changing the GenAI in order to develop smarter, interoperable, and context-aware hospital information systems. The obtained results underline the importance of using domain-adapted language models to maximize the effectiveness of medical processes, reduce administrative burdens, and improve care delivery to patients. In the long run, the integration of such smart systems

into the actual hospital environments can open a new dawn of automation in healthcare whereby unstructured data will be automatically used to generate actionable data. This effort can be expanded on in future research with multimodal data streams, explainability AI systems, and real-time deployment systems and in this way progress to an autonomous but ethically responsible digital health ecosystem.

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ICU Bed Prediction Model using Ensemble Learning

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Abstract. Accurate forecasting of Intensive Care Unit (ICU) bed occupancy is a critical component of hospital capacity planning and emergency preparedness. This study proposes a data-driven forecasting framework employing advanced ensemble learning techniques to predict short-term ICU utilization based on routinely collected hospital operational data. Temporal dependencies within the dataset were modeled through the incorporation of lag features, rolling statistical measures, exponentially weighted averages, and weekday encoding. The predictive framework integrates three gradient-boosting algorithms—Light Gradient Boosting Machine (LightGBM), Extreme Gradient Boosting (XGBoost), and Categorical Boosting (CatBoost)—combined through a Stacking Regressor with Linear Regression as the meta-learner. Experimental evaluation on the Michigan Hospital Capacity Tracking dataset demonstrates that the proposed model achieves a Mean Absolute Error (MAE) of 37.72 and a Root Mean Squared Error (RMSE) of 60.34, representing an improvement of approximately 20% over baseline persistence models. The ensemble’s ability to efficiently capture nonlinear temporal patterns without reliance on patient-level electronic health records highlights its applicability for real-world hospital management systems. The proposed methodology offers a scalable and interpretable solution capable of supporting proactive decision-making in resource-constrained healthcare environments.

Keywords. ICU Capacity Prediction; Ensemble Machine Learning; Time Series Modeling; Healthcare Resource Management; Predictive Analytics

1. Introduction

Management of Intensive Care Unit (ICU) resources is a cornerstone to resilience and responsiveness of healthcare systems. Imbalances in demand and capacity in the ICU may result in critical bottlenecks in patient care during times of high patient influx, such as pandemics, seasonal disease increase, or mass emergencies. Hospitals have traditionally used either manual scheduling or heuristic planning or a mere statistical extrapolation in capacity forecasting. These techniques can be, however, less flexible and less accurate to handle the quickly changing demand trends in the dynamic healthcare environment.

The latest developments in the field of machine learning (ML) have allowed the implementation of data-driven solutions to predict the trends of occupancy in hospitals, staffing management, and resource use. Although the use of techniques like Autoregressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM) networks in time series modeling have been used in the healthcare sector, they are either constrained by the assumption of linearity (ARIMA) or through high computation costs and complexity in tuning (LSTM). Moreover, numerous previous studies rely strongly on granular electronic health record (EHR) data which is not always inter-institutional and real-time.

To overcome these problems, this paper suggests a gradient boosting-based ensemble model to predict short-term ICU bed capacity based on regularly gathered operational data of the hospital. The presented model combines Light Gradient Boosting Machine (LightGBM),

Extreme Gradient Boosting (XGBoost), and Categorical Boosting (CatBoost) models in a stacked ensemble framework, which is simultaneously optimized by the help of a Linear Regression meta-learner. The structure enables the model to support nonlinear temporal dependence, efficient management of missing or categorical data, and trade-off accuracy and computational efficiency.

The model was improved by using temporal feature engineering methods such as lag variables, rolling averages, exponentially weighted means, and weekday encoding so that it was more able to learn short-term occupancy patterns. The system was tested on the Michigan Hospital Capacity Tracking dataset that is a realistic operating environment in a hospital.

The suggested structure has a better predictive performance than the classical baselines with significant decreases in Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). The interpretability, scalability, and low computational cost of it make it an appropriate choice in real-time integration into hospital management dashboards, allowing predictive resource planning and evidence-based operational decision-making.

2. Problem Definition and Research Scope

The main aim of this research is to come up with a predictive modeling system that will be able to predict the short-run bed occupancy of the Intensive Care Unit (ICU) in a hospital based on the regularly gathered operational data in the hospital. This is in contrast to the patient-level prediction systems, which are based on specific clinical parameters, and instead, the indicators are at the aggregate level (i.e. ICU use, inpatient hospital admissions, and ventilator usage) that are easily accessible at most healthcare institutions.

The formulation of the problem is as a supervised regression task with the target variable looking at the number of occupied ICU beds on a particular day, predictors being the past measures of utilization as well as the calculated temporal measures. The system is intended to forecast the occupancy of the ICU a few days in advance to help hospital administrators to take proactive decisions regarding staffing, admissions, and allocation of equipment.

In order to do that, the ensemble of the machine learning models consisting of Light Gradient Boosting Machine (LightGBM), Extreme Gradient Boosting (XGBoost), and Categorical Boosting (CatBoost) was created and the stacked generalization approach was used to optimize it. Such a set up enables each of these models to identify different things about the data distribution, such as LightGBM to effectively model large, tabular data; XGBoost to effectively minimize errors using regularized boosting; and CatBoost to effectively treat categorical data and avoid overfitting. The combination of these predictions is a Linear Regression meta-learner that gives the final forecast.

Temporal feature engineering is also included in the framework to model the dependencies on the hospital utilization data. The lag features record short term memory effects, the rolling averages reduce random variations, the exponentially weighted means are more focused on the recent trends, and the weekday encoding is to explain the repetitive nature of operations of a company.

The study has a narrow scope of predicting ICU occupancy only using operational datasets without the use of other covariates including epidemiological data or patient-level data. This controlled limitation indicates the validity of the use of a lightweight, interpretable model in practical hospital information systems without any extra data integration overheads.

3. Current Trends in Hospital Capacity Forecasting

The recent development of analytics in healthcare has been observed to turn towards more of a shift towards data-centered and forecasting model solutions to hospital capacity forecasting. Traditional statistical models such as linear regression and autoregression have been slowly phased out or improved with state-of-the-art machine learning and deep learning models capable of characterizing nonlinear and multivariate relationships in hospital operations data.

It has been studied in a number of works that apply Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) to predict patient admission and bed occupancy using their ability to embrace long-term temporal dependencies. However, neural architecture typically requires enormous datasets, massive computational power, and parameter optimization, and thus are not as practical in real time in resource constrained healthcare environments. Alternatively, hybrid methods that make use of autoregressive models and machine learning algorithms have been proposed as well to increase interpretability and adaptability.

More recently the focus has shifted to ensemble-based models (especially Gradient Boosting Machines (GBM), Extreme Gradient Boosting (XGBoost), and Light Gradient Boosting Machine (LightGBM)) as being more competent with structured time-series data, particularly by virtue of being more competent. Advantages of these models are that they can train faster; they are able to automatically deal with missing values and they have a high level of generalization. Their ability to incorporate both time-related and categorical characteristics has predetermined their suitability to short-horizon hospital occupancy forecasting, employee scheduling, and supply chain management.

In general, the newly developed body of research suggests the growing interest in scalable, interpretable, and computationally effective solutions, which can be easily integrated into hospital management systems to facilitate the prediction of decisions.

4. Model Architecture

The presented ICU occupancy prognostication system is designed in a structured architecture, which integrates data preprocessing, temporal feature engineering, model training, and ensemble-driven prediction. The framework is designed to derive temporal dependencies, nonlinear correlations and operational patterns of hospital utilization data by a sequence of algorithmic and statistical transformations.

The data used is the Michigan Hospital Capacity Tracking System, which includes the daily operational data, which includes the use of the ICU bed, the amount of inpatients, and the use of ventilators. Every record is the status of a day in hospital on a day-by-day basis. In order to make everything consistent, all numerical features were transformed into floating point format and missing values were interpolated with forward filling keeping the continuity in each feature time series and maintaining the temporal order.

The dataset was then cleaned followed by temporal feature engineering to make the data predictively rich. There were three major feature categories that were obtained:

Lag Features: These are the occupancy of the past days so as to encode the short-term memory of the model. As a mathematical expression, to have a target variable y_t (ICU beds used on day t), the lag features may be defined as:

$$y_{t-k} = \text{ICU\_Used at day } (t-k), k=1, 2, \dots, 7 \quad (1)$$

Rolling Averages: To smooth noise and capture medium-term trends rolling standard deviation and rolling mean were calculated over fixed windows:

$$roll_n(t) = 1/n \sum_{t=0}^{n-1} y \quad (2)$$

To conduct the present study, rolling mean functions were calculated on both three and seven days windows to reflect short-term and weekly changes in the use of the ICU. These characteristics were referred to as three-day and seven-day rolling averages of the ICU occupancy. 3. Exponentially Weighted Mean (EWM): Exponential smoothing was used to help it be sensitive to new changes:

$$EWM(t) = \alpha y_t + (1 - \alpha)EWM(t-1) \quad (3)$$

where $\alpha = 2 / (1 + \text{span})$, and span was implemented to be 3.

Cyclical Encoding: To capture periodic patterns of workflow in the hospitals, weekday encoding was included. *Pandas* was used to extract the day of the week (0-6) in the date column through the *datetime* library.

Following the construction of the features, the input matrix *X* included the lag features, rolling features and statistical features, whereas the target variable *y* was the real ICU occupancy (ICUUsed). To ensure data leakage was avoided, the data was dichotomised chronologically in a ratio of 80: 20 and *shuffle=False* in the *scikit-learn* train-test split function.

The predictive framework uses a stacked ensemble model comprising of three gradient boosting algorithms including Light Gradient Boosting Machine (LightGBM), Extreme Gradient Boosting (XGBoost), and Categorical Boosting (CatBoost) and Linear Regression meta-learner. Every base learner is modeled as an ensemble of decision trees $f_m(x)$ with each tree being trained to minimize a differentiable loss function $L(y, y)$ by stage-wise additive training:

$$\hat{y}_t = \sum_{m=1}^M v f(x_t) \quad (4)$$

where *m* is the learning rate.

Trees in LightGBM are grown in the leaf-wise mode as opposed to the level-wise mode. In every iteration, the algorithm picks the leaf that minimizes the loss the most to be split and the algorithm can converge faster and decrease the error. A split gain is calculated as follows:

$$Gain = GL^2/(HL + \lambda) + GR^2/(HR + \lambda) - (GL + GR)^2/(HL + HR + \lambda) - \gamma \quad (5)$$

In which *G* and *H* are the first and second-order gradient of the loss, *l* is the L2 regularization term, and *g* is used to enforce averse splits between leaves.

XGBoost is a supplement to this, building level-wise trees where the loss minimization uses second-order Taylor approximation, which provides efficient regularization of shrinkage and subsampling. CatBoost, however, employs ordered boosting and statistical target encoding to effectively deal with categorical variables without overfitting/bias.

A meta-learning layer combines the predictions of the base learners in a Linear Regression model which determines the best coefficients *w_i* to combine the base outputs:

$$\hat{y} = \sum_{i=1}^I w_i y_i + b \quad (6)$$

The *scikit-learn* Stacking Regressor was applied in implementation to combine the three underlying models with the meta-learner in a manner that ensures consistency of cross-validation and minimizes overfitting. The last model was trained with 1000 estimators per base learner and 0.05 learning rate. The measures of evaluation, Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) measure the difference between actual and predicted occupancy values:

$$MAE = (1/n) \sum |y_i - \hat{y}_i|, \quad RMSE = \sqrt{(1/n) \sum (y_i - \hat{y}_i)^2} \quad (7)$$

A low value on these measures implies greater predictive accuracy. Lastly, the predictions of the model that had been trained were plotted using an Actual vs Predicted plot, which allowed a clear comparison between actual occupancy trend and the model predictions. This tight fit of these curves confirmed the learning capability of the model to short-term fluctuations but general stability. In general, this architecture is a hybrid, interpretable, and computationally efficiency design, which manages to combine statistical feature extraction and current ensemble learning to forecast ICU occupancy using operational datasets.

5. Results and Model Evaluation

The developed ensemble regression framework, integrating LightGBM (Light Gradient Boosting Machine), XGBoost (Extreme Gradient Boosting), and CatBoost (Categorical Boosting), was trained and evaluated on the Michigan Hospital Tracking dataset. The dataset contained time-stamped information on hospital resources such as ICU bed usage, mechanical ventilator availability, and inpatient occupancy rates, forming the basis for predictive modeling of ICU utilization.

An 80:20 chronological split was applied, reserving the last 20% of the dataset for testing. Input features included both static (e.g., hospital capacity) and dynamic temporal indicators, such as 7-day lag features, rolling averages, and exponentially weighted means (EWM). These engineered features enabled the model to capture temporal dependencies and smoothed fluctuations typical of hospital data, thereby reducing noise-induced variance.

Model performance was evaluated using Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). The ensemble achieved an **MAE of 8.08** and an **RMSE of 11.61**, outperforming baseline models such as standalone LightGBM and linear regression, which exhibited higher error metrics. The improvement can be attributed to the stacking architecture, where predictions from individual models are combined through a Linear Regression meta-learner, effectively capturing complementary strengths of each gradient boosting technique.

Visualization of actual versus predicted ICU usage demonstrated that the ensemble accurately tracked temporal trends, particularly during peak occupancy periods, indicating strong model generalization. The inclusion of rolling mean and EWM features significantly improved responsiveness to short-term surges while preventing overfitting.

Comparative testing across models showed that LightGBM offered superior performance due to its leaf-wise tree growth algorithm, which enables deeper exploration of complex non-linear relationships without increasing bias. When combined with XGBoost and CatBoost, the resulting hybrid model produced smoother predictions and enhanced stability across varying hospital load conditions.

6. Discussion and Future Scope

The experimental results, while demonstrating satisfactory predictive accuracy, show that the ensemble's performance can still be enhanced to achieve parity with state-of-the-art hospital resource forecasting models. The obtained **MAE of 8.08** and **RMSE of 11.61** indicate that although the model effectively captures general occupancy patterns and temporal trends, it occasionally underestimates abrupt spikes in ICU usage.

This limitation primarily arises from the absence of external covariates—such as patient inflow rates, disease prevalence, and emergency admission data—which are known to improve sensitivity to sudden demand fluctuations.

Another contributing factor is the restricted dataset granularity. The Michigan Hospital Tracking dataset, while reliable, lacks minute-level or department-specific updates that could provide finer control signals for model calibration. Additionally, the lag and rolling average features, though effective in stabilizing predictions, tend to smooth out extreme variations, thereby reducing responsiveness to short-term anomalies.

To improve predictive precision, future work should incorporate multivariate exogenous variables such as regional infection trends, weather data, and public health alerts. Integrating temporal attention mechanisms **or** hybrid deep learning architectures like CNN-LSTM (Convolutional Neural Network–Long Short-Term Memory) networks could further enhance the model's ability to capture long-term dependencies and nonlinear patterns. Moreover, a real-time retraining pipeline leveraging online learning could continuously adapt the model as new hospital data becomes available, ensuring higher accuracy and resilience in dynamic healthcare environments.

These refinements would advance the model beyond its current capabilities, enabling more proactive and resource-efficient hospital management through real-time decision support.

7. Conclusion

This work introduces a machine learning system based on an ensemble that predicts the occupancy of the ICU bed based on the temporal and operational data of the hospital. The model uses three innovative gradient boosting algorithms such as LightGBM, XGBoost, and CatBoost stacked atop each other and the findings of them are linearly averaged with a meta-regressor to minimize errors and maximize the robustness of the model. The framework can also model the temporal dependence by incorporating lag features, rolling averages and exponentially weighted mean transformations, and it is as such, the framework can model both smooth and short-term trends in the utilization of the hospital.

The ensemble that was proposed achieved a Mean Absolute Error (MAE) of 8.08 and Root Mean Squared Error (RMSE) of 11.61 that were significantly better than the baselines of single-model purchases. The results demonstrate the effectiveness of heterogeneous collections of gradient boosting algorithms in addressing healthcare prediction problems since each of the models has its benefits that include the capability of LightGBM to work with large volumes of numerical data, the capability of XGBoost to control models, and the capability of CatBoost to deal with categorical data without having to pre-process them. The synergy between the two offers predictable and scalable predictive solution, which can be used in the resource planning of a hospital. Regarding its performance, it is possible to increase the model's predictive accuracy by introducing additional data roots, including real-time patient inflow rates, emergency department statistics, and epidemiological indicators. The spatial characteristics such as transfers between hospitals and the surge of cases in the region would also be included in improving the model. Besides, hybrid deep learning designs like Bi-LSTM (Bidirectional Long Short-Term Memory) or Transformer-based designs can also be used in the future to increase the temporal resolution, and adaptive learning.

Overall, the paper identifies the potential of ensemble-based predictive analytics in dynamically changing healthcare facilities. They can apply the framework as an underpinning of real-time hospital decision-support systems that can give early warnings on ICU congestion and assist the policymakers in proactive capacity emanation and ultimately enhancing patient outcomes by the means of operations controlled by data.

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A Review of Deep Learning Approaches in Postpartum Depression Detection

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Abstract. The Postpartum depression (PPD) is a significant mental health concern affecting mothers worldwide, yet it often remains underdiagnosed due to stigma and limited clinical screening. Deep learning (DL) has shown remarkable potential for automating PPD detection from text, speech, physiological signals, and other modalities, but current research remains fragmented. Many high-performing DL architectures, such as CNN-LSTM and Bi-LSTM models, are designed as black-box systems, lacking integrated explainability, which limits their clinical trust and adoption. In addition, few frameworks specifically target early detection of PPD, despite growing attention to maternal health risks more broadly. Over-reliance on single screening tools like the EPDS or PHQ-9 further restricts diagnostic reliability, while existing studies often face a trade-off between performance and interpretability. Moreover, limited exploration of multi-class classification hampers the ability to capture varying severity levels of PPD. This review consolidates the state of deep learning applications for PPD detection, analyzing existing models, datasets, and evaluation strategies. It also highlights key research gaps and proposes directions for developing accurate, interpretable, and clinically viable DL frameworks that can enable reliable early detection of postpartum depression.

Keywords. Postpartum Depression, Deep Learning, Early Detection, Explainable AI, Mental Health, Clinical Decision Support, Multi-class Classification

1. Introduction

Characterized by consistent sadness, fatigue, loss of interest, Postpartum Depression (PPD) is a mental health condition which is prominent for women following childbirth, which has a global incidence of 10-20% among the recent mothers, PPD leads serious repercussions to infant's development, mother's and infant's mental health, and family dynamics if left untreated. Detection of PPD, despite of its significance, lies on a self-reporting and culturally sensitive subjective questionnaires such as Edinburgh Postnatal Depression Scale (EPDS) or the Patient Health Questionnaire (PHQ-9).

With the advancements in the field of artificial intelligence, machine learning and deep learning, these methods are actively leveraged for automation and enhancing the diagnosis process of such mental health disorders. Since the high-dimensional dataset is complex and actively contains hierarchical patterns, deep learning in particular provides promising results data — making it suitable for analyzing behavioral, linguistic, and physiological indicators of PPD [3]. The “Black Box” nature which lacks transparency, interpretability and validation on diverse dataset of deep learning models impedes their clinical adoption and restricts their integration with real-world maternal healthcare system.

The Review paper exclusively focuses on **deep learning-based approaches for PPD detection**, outlining recent trends, model architecture, data modalities while also highlighting key limitations and proposing direction for explainable, hybrid and multimodal frameworks.

2. Literature Review

This section of the review paper focuses on the already applied work of deep learning in detection and prediction of postpartum depression (PPD). The review is structured according to data modality which includes textual, physiological, and multimodal categories, succeeded by a summary dataset utilized and comparative table for showcasing the representative studies and emphasizing on limitation and methodological deficiencies.

2.1. Overview of the Field

Computational identification of postpartum depression has evolved from statistical models to machine and deep learning models which can learn hierarchical representation which is present in the high dimensional dataset. Reviews on machine learning approaches to PPD highlights consistent potential to improve early identification along with emphasizing on the issue of dataset heterogeneity, limited external validation which are required for clinical adoption. Recent comprehensive reviews suggests the need for more explainable and multimodal deep learning research in perinatal mental health.

2.2. Text- based Deep Learning Approaches

Amongst the widely used data for automating the screening process for detection of depression , textual sources such as clinical notes, forum entries, social media played a huge role because they are abundant and can capture real -world expressions. Studies used CNNs and RNNs models to extract semantic and temporal linguistic patterns, some of the recent studies also leveraged transformed-based models with contextual encoders like BERT, RoBERTa which were responsible to improve sensitivity for subtle sentiment and contextual shifts.

- **CNN/LSTM hybrids and attention mechanism:** For depression detection task, we use a hybrid model which are combination of CNN and BiLSTM models, as CNN models are used for local n-gram detection while BiLSTM use for sequential context which together achieves a competitive performance on the dataset. The models can further be improved by addition of attention layers which assigns importance weights to token or phrases. For general depression detection and related tasks, attention -based CNN -BiLSTM models have proved to provide with strong results.
- **Transformer- based fine-tuning:** Recent studies shows that fine tuning pretrained transformer encoders with the ability to capture pragmatic markers such as self-referential language, hopelessness cues on a perinatal-specific datasets like maternal forums, postpartum tweet subsets yielded higher accuracy.

2.3. Physiological and Behavioral Deep Learning Models

These signals provide time- series data that can be complemented on subjective textual reports, these signal modalities include, heart rate variability (HRV) , sleep / wake patterns, EEG reports.

- **CNNs & CNN- LSTM hybrids for temporal signals :** CNN models are specialized for time series datasets as they can be modelled for local temporal and spatial patterns in the dataset, this is often paired with a LSTM model forming and Hybrid deep learning model as LSTM helps in capturing the long- range temporal dependencies inside the dataset, recent studies suggest that these hybrid models are showcasing promising results by distinguishing between depressed and non – depressed postpartum women with promising results.
- **EEG -based approaches:** Multichannel EEG are treated as spatial -temporal matrices, which can exploit both cross-channel spatial patterns and temporal dynamics by the Deep Learning convolutional architectures .

- **Limitations:** Physiological studies often suffer from the small sample groups sizes, sensor variation for different patients, and effects like sleep deprivation, medication, physical postpartum recover which complicates the generalization. Moreover label noises often occur in the dataset due to questionnaire-based screening for PHQ and EPDS

2.4. Multimodal Deep Learning

The postpartum state of an individual can be represented completely by multimodal fusion combining the textual content, behavioral traces like phone usage, mobility, sleep and physiologic sensors. There are 3 stages of deep learning-based fusion strategies which are early fusion , intermediate/ attention based fusion and late fusion.

- **Representative multimodal framework:** The early detection performance of the model can be improved by integration of social media text with smartphone collected behavioral metrics. The increase in performance can be seen through better and improved AUC scores and recall metrics when the modalities were complementary.

- **Fusion methods and interpretability:** The clinical explainability of the model can be improved by using an attention based cross modal fusion layers which can allow the model to weight the modalities dynamically and can be probed to reveal which signals drove a prediction at a given timepoint.

2.5. Dataset Used in PPD & Related Depression Research

Postpartum depression deep learning studies reply on varied data sources; the heterogeneity of these dataset is a recurring challenge for the evaluation process

- **Self Report questionnaire & EHRs:** Most of the clinical studies reply on the questionnaire scores of EPDS and PHQ -9 in the cohort or primary care EHRs as labels. Models trained on EHRs are tends to predict PPD risk with reasonable accuracy, but many are limited by the HER coding practices and missingness.

- **Social Media and Forums:** Publicly available data such as twitter , reddit post and maternal forums are utilized as a data source for text- based models. Accurately labeling such data in challenging despite of the data being large and temporally rich.

- **Notable dataset gaps:** There is a shortage of large standardized multimodal PPD datasets along with being clinically verified diagnosed. Public datasets are also limited by geographic and cultural diversity, constraining cross- population generalizability

2.6. Comparative Analysis of Representative Deep – Learning Studies

Table represents and summarizes the Deep Learning research on detection of PPD , the Table 1. aims to present the model family, data modality, dataset characteristics and reported outcomes.

Synthesis : Common Strengths and Weaknesses

- **Strengths observed amongst the studies:**
 - **Improved sensitivity and scalability :** Deep learning models , which are based on transformer and CNN- LSTM hybrids , consistently outperforms the traditional ML models on the available similar datasets.
 - **Ability to exploit temporal and contextual cues:** Deep learning models , specifically the RNNs and LSTM models are capable of capturing the sequential and contextual signals in physiological streams and textual narratives, therefore allowing early detection signs.

Table 1. The model family, data modality, dataset characteristics and reported outcomes

Author(s)	Year	Title	Methodology	Key Finding	Limitation
Qi et al.	2025	Prediction of postpartum depression in women: development and validation of multiple machine learning models	Developed predictive models using biopsychosocial features from 1138 perinatal women. Used 7 feature selection methods (e.g., LASSO, RF, SVM-RFE) and 6 ML algorithms (e.g., LR, ANN). SHAP used for explainability.	LR and ANN models performed best (AUC: 0.801–0.858). Postnatal predictors (e.g., mother-in-law care) significantly improved performance. Developed interpretable tools like nomograms and risk calculators.	Single-center study with no external validation; cultural specificity (e.g., mother-in-law's role); lacks first-trimester data.
Jose et al.	2025	An Integrated Context-Aware Adaptive Meta-Learning System for Accurate Risk Estimation of PPD	CAML framework using LSTM, CNN, XGBoost, Gradient Boosting with SHAP & LIME; incorporates sensor and context data	Achieved 98.7% accuracy; model is interpretable and context-aware, showing high clinical relevance	High complexity; requires sensor and contextual data that may not be universally available
Lin & Zhou	2025	A method for predicting postpartum depression via an ensemble neural network model	Ensemble of FCNN and DNN with dropout; interpretable structure based on weights and architecture	Achieved accuracy of 93.3%, F1-score of 0.948; balances interpretability and generalizability	Limited to tabular/clinical data; no deep interpretability tools like SHAP or LIME used
Wani et al.	2023	Depression Screening in Humans With AI	Social media-based depression detection	Accuracy up to 99.02%; good for general depression	Not specific to PPD; focuses on general depression,

		and Deep Learning Techniques	using hybrid features (TF-IDF, Word2Vec) + CNN + LSTM	detection on Facebook, YouTube, Twitter	lacks clinical or physiological input
Shivaprasad et al.	2024	Explainable ML methods to predict postpartum depression risk	KNN, Stack Model + Explainable AI (LIME, SHAP, ELI5, Anchor); used Kaggle dataset	Accuracy up to 97%; focused on explainability in PPD prediction; highlights features impacting prediction	No deep learning; lacks temporal modeling like LSTM; limited data diversity
Saleh et al.	2024	An Explainable Deep Learning-Enhanced IoMT Model for Effective Reduction of Maternal Mortality Risks	Uses (CRNN) within an IoMT framework to predict maternal risk on both regional and patient datasets and LIME for model explainability.	The CRNN model achieved high accuracy for regional (92.6%) and patient (80.3%) risk prediction.	The model's dependence on high-quality data and its unproven generalizability.
Onem et al.	2024	Conducting Maternal Health Risk Analysis with Deep Learning	Applied TabNet deep learning model, to perform maternal health risk analysis across eight categories.	GAN-augmented data achieved higher accuracy, including Preterm birth (+2.2%) and others	performance depends on the manual tuning of hyperparameters. Also, The initial dataset was small.
Nakamura et al.	2024	Early identification of postpartum depression using machine learning	compared several machine learning algorithms, ultimately selecting the Balanced GBDT	The Balanced GBDT model proved most effective. It achieved an accuracy of 78.6% and an AUC of 0.83.	The model produced a low Positive Predictive Value (PPV), which is a common challenge in PPD research

Valarmathi et al.	2024	A deep learning-based hybrid model for maternal health risk detection and multifaceted emotion analysis in social networks	hybrid deep learning framework called MHRFD-DLA, which integrates CNNs, LSTM networks and an attention mechanism.	It achieved an overall accuracy of 98.4%, precision of 97.6%, recall of 95.6%, and an F1-score of 96.6%.	Need for more advanced data fusion techniques to handle more modalities (like images).
Taofeeq et al.	2023	Deep hybrid model for maternal health risk classification in pregnancy: synergy of ANN and random forest	proposes a deep hybrid model, MaternalNET-RF, that combines an ANN with a Random Forest (RF) algorithm	The hybrid MaternalNET-RF model achieved a high accuracy of 94.9%, outperforming the individual ANN (71.3%) and RF (88.6%) models	use of a small dataset from a single geographical area (rural Bangladesh), which may limit the model's generalizability
Zhang et al.	2025	Interpretable Machine Learning Model for Predicting Postpartum Depression: Retrospective Study	Single-hospital dataset; retrospective design; sample imbalance and external validity not tested.	XGBoost AUC = 0.849; 6 main predictors identified; enhanced screening and model explainability for PPD.	Single-hospital dataset; retrospective design; sample imbalance and external validity not tested.
Lilhore et al.	2024	Prevalence and risk factors analysis of postpartum depression at early stage using hybrid deep learning model	Designed a hybrid multimodal deep learning architecture combining Bi-LSTM and Transfer Learning modules using 15 k records; benchmarked against	Best configuration = 92.4 % accuracy; model fused demographic and financial predictors for early identification of PPD risk.	Limited dataset size; class imbalance; deep features less interpretable.

			multiple DL baselines.		
Anaduek a et al.	2025	Leveraging artificial intelligence in the prediction, diagnosis and treatment of depression and anxiety among perinatal women in low- and middle- income countries: a systematic review	Followed PRISMA guidelines (2010–2024); analyzed 29 studies across clinical, digital, and public AI/ML interventions; mixed method and narrative review.	AI/ML mainly applied to diagnosis tasks; high accuracy but few models for long-term management or real-world validation.	English-only studies; heterogeneous datasets; lack of standard evaluation protocols.
Liu et al.	2025	A machine learning– based framework for predicting postpartum chronic pain; a retrospective study	Retrospective analysis of 3,589 women after childbirth with 36 variables; LASSO for feature selection; XGBoost model validated with resampling techniques.	XGBoost AUC = 0.857 (95 % CI 0.814– 0.875); identified pain predictors; supports better pain management after delivery.	Retrospective Chinese dataset; sampling bias; requires external validation.
Zhang et al.	2025	Interpretable Machine Learning Model for Predicting Postpartum Depression: Retrospecti- ve Study	Single- hospital dataset; retrospective design; sample imbalance and external validity not tested.	XGBoost AUC = 0.849; 6 main predictors identified; enhanced screening and model explainability for PPD.	Single- hospital dataset; retrospective design; sample imbalance and external validity not tested.

- **Persistent weakness and barriers**

- **Explainability gap:** Present performing models are opaque in nature, since they have insufficient use of XAI techniques like SHAP, LIME, attention visualization which results in reduced clinical trust on practical implementation of the model .

- **Dataset Limitation :** The sample size used for training of the model are small in nature with less amounts of patients along label noise for social-media derived labels like reddit and twitter posts .

- **Limited early- detection orientation :** Most of the present studies are performed on post-hoc classification of recorded PPD cases. Which should be build on longitudinal early-warning signs .

2.7. Implication for Future Research

As per the above study, the most impactful steps are :1) Creating a large, longitudinal, clinically labeled multimodal dataset; 2) Integrating explainability module in the deep learning architecture for better understandability of the model ;3) Validating model across multi- center and cross cultural cohorts; 4) Focusing on early warning detection systems.

Several recent works suggest positive shift in the field towards clinical readiness through their work proposing explainable ML and translational validation pipelines.

3. Research Gap

While there has been rapid progress, several research limitations still exist in current deep learning approaches for PPD detection:

- 1). **Lack of Integrated Explainability:**

Most of the high-performing DL models remain opaque, which lack interpretability tools like SHAP, LIME or even attention visualization. This creates an obstacle in the clinician trust and model transparency.

- 2). **Insufficient Early Detection Focus:**

Many models predict PPD using post-diagnosis data. Early-stage prediction frameworks that are trained on pre-onset indicators are scarce.

- 3). **Limited Data Diversity:**

Current datasets are many times small, imbalanced or region-specific, which restricts model generalizability across a diverse maternal population.

- 4). **Over-Reliance on Textual Data:**

While text-based models still dominate, few studies leverage physiological and behavioral signals that can capture real-time mood fluctuations.

- 5). **Performance–Interpretability Trade-Off:**

Complex architectures (e.g., Transformer ensembles) offer high accuracy but poor transparency, on the other hand, simpler interpretable models lack predictive strength.

- 6). **Underexplored Multimodality:**

Integration of time-series physiological data with textual or behavioral information still remains limited, despite its potential to enhance early detection accuracy.

4. Discussion and Future direction

Future studies in deep learning-based PPD detection should focus on the following areas to address the issues noted:

1). **Explainable Deep Learning Frameworks:**

By visualizing feature contributions and decision justification, the incorporation of interpretability mechanisms like SHAP, LIME, or Grad-CAM into CNN-LSTM models can further improve clinical acceptability.

2). **Early Detection-Oriented Architectures:**

Pre-symptomatic indicator identification should be the main goal of models. Preventive actions will be made possible by the analysis of sequential postpartum data.

3). **Data Augmentation and Federated Learning:**

By employing GANs or federated learning frameworks to generate synthetic data, data scarcity can be lessened while maintaining patient privacy.

4). **Hybrid Architectures:**

These combine CNN-LSTM pipelines with interpretable layers (such attention-based fusion or XGBoost) to balance explainability and predictive accuracy.

5). **Clinical Collaboration:**

Using real-world hospital datasets for multi-center validation can increase robustness and guarantee that the models accurately represent clinical variability.

6). **Towards Clinical Deployment:**

Research and practice will be brought together with the creation of interactive dashboards for clinicians that provide risk scores, attention maps, and other influencing factors

5. Conclusion

This review analyzed the recent advancements in deep learning-based approaches for Postpartum Depression detection. While models like CNN, LSTM and Transformer demonstrate high predictive performance, their lack of transparency and limited multimodal integration still is a major barrier to clinical adoption of this approach. When we will be able to bring together explainability and performance through hybrid, interpretable and data-driven architectures, it would represent the next frontier for maternal mental health AI research. Building trust through explainable deep learning will be crucial in transforming automated PPD detection from a research concept into a clinically reliable diagnostic aid.

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Recent Trends in Software Development Life Cycle (SDLC) in Healthcare

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Abstract. Software Development Life Cycle in the healthcare industry focuses on secure, flexible, patient-centered solutions. Smart contracts and blockchain integration guarantee data privacy, interoperability, and trust, all of which are crucial for medical workflows. Personalised care, real-time monitoring, and predictive analytics are made possible by the use of digital twin technology. Model-Based Software Engineering enhances design integrity, while Agile and Hybrid Agile models promote adaptability to changing healthcare needs. Automation powered by AI speeds up the early stages of the SDLC and simplifies requirement analysis. Hospital systems and medical device development are further optimised by lean and sustainable approaches. Overall, these trends show how healthcare software is moving toward being smarter, more reliable, and designed to last in a sustainable way.

Keywords. Software Development Life Cycle (SDLC), Agile, Artificial Intelligence, Digital Twin, Sustainability, Predictive Maintenance

1. Introduction

The System Development Life Cycle (SDLC) serves as a structured framework guiding software engineering processes from conception to deployment and maintenance. Recent years have witnessed rapid technological evolution and an increased demand for adaptive, secure, and intelligent systems. Traditional SDLC models, while foundational, have been progressively transformed through Agile, Hybrid, and AI-augmented methodologies. This paper synthesizes insights from several studies published between 2020 and 2025, encompassing areas such as healthcare, manufacturing, sustainable computing, and predictive analytics. By combining structured approaches with emerging technologies, the modern SDLC aims to achieve faster delivery cycles, improved quality, and enhanced adaptability to dynamic user and business requirements.

2. Evolution of SDLC Models

Classical SDLC models, including Waterfall, Spiral, and V-Model, have long established the foundation for systematic software development. However, the increasing complexity of systems and rapid shifts in user requirements led to the emergence of iterative and agile paradigms. Agile methodologies promote collaboration, adaptability, and customer engagement, while hybrid approaches blend structured validation with flexibility. Recent literature (Kyeremeh, 2021; Hossain, 2023) emphasizes decision matrix-based selection for optimal methodology, reinforcing that no single model fits all project contexts. This adaptive approach aligns with modern organizational priorities for risk reduction, continuous delivery, and efficient lifecycle management.

3. Integration of AI and Automation in SDLC

Artificial Intelligence (AI) has emerged as a transformative force in SDLC. Research by Voruganti (2024) and Nistala (2022) underscores the role of AI-driven systems—from generative AI agents managing code to production pipelines to intelligent frameworks automating requirement engineering. These advancements enable 'quality at speed' through automation of repetitive tasks and predictive analytics. The integration of reinforcement learning, natural language processing, and machine learning models within SDLC phases ensures improved requirement accuracy, optimized testing, and faster deployments.

4. Sustainable and Green Software Development

The intersection of sustainability and software development has become a critical research area. Studies by Mirzaei (2024) and Firmansyah et al. (2024) explore integrating green computing principles and sustainable design practices into SDLC frameworks. These works advocate for eco-efficient methodologies that reduce digital carbon footprints and align with UN SDG 12 on responsible consumption. Sustainable UI/UX design, energy-efficient coding, and lifecycle-conscious resource management are emerging trends redefining how software projects contribute to global sustainability efforts.

5. Digital Twins and Predictive Systems

The Digital Twin concept, highlighted by Vallée (2023), introduces dynamic virtual representations of real-world systems, particularly in healthcare and manufacturing. When combined with SDLC frameworks, digital twins enable real-time monitoring, simulation-based validation, and predictive maintenance. Similarly, Goyal (2022) demonstrates how predictive maintenance models enhance software lifecycle management by preempting failures and optimizing updates, transforming SDLC from reactive maintenance to proactive intelligence-driven evolution.

6. Agile and Lean Methodologies in Regulated Industries

Gadde and Kalli (2020) examine the integration of Lean principles within SDLC in regulated domains like medical device manufacturing. The hybrid Lean-SDLC approach balances compliance with flexibility, emphasizing continuous improvement and waste elimination. This model has proven especially beneficial in environments constrained by documentation-heavy frameworks such as FDA and IEC 62304, ensuring quality without compromising efficiency.

7. Security and Risk Management in Modern SDLC

The growing complexity of software ecosystems has heightened the importance of risk management and cybersecurity integration. Adriani et al. (2024) highlight ISO 16085:2021 as a framework for mapping risk activities across SDLC stages, promoting proactive mitigation. Maidin et al. (2025) extend this by focusing on software security within Agile and Hybrid Agile models using bibliometric analysis. Both studies underline the necessity of embedding security practices early in the development cycle ('shift-left security') to achieve resilient and sustainable software systems.

8. Case Studies and Applications

Practical implementations across sectors validate these theoretical advancements. Vallée (2023) and Okoromi (2021) illustrate healthcare system innovations through digital twins and hospital management systems, while Alif Faridalthaf et al. (2022) apply SDLC to jewelry manufacturing for inventory optimization. Such diverse use cases reinforce SDLC's adaptability beyond software-centric projects—proving its relevance in operational, predictive, and decision-support systems.

9. Conclusion

This study consolidates key findings from contemporary SDLC research between 2020 and 2025, revealing an ecosystem increasingly shaped by AI, automation, sustainability, and agility. Emerging models demonstrate a paradigm shift toward intelligent, data-driven, and environmentally responsible development processes. Future SDLC frameworks are expected to emphasize continuous adaptation, ethical AI integration, and cross-domain interoperability, ensuring robust, sustainable, and secure digital ecosystems.

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A Systematic Review on Advanced Multi-Channel and Wearable Surface Electromyography Systems with AI-Driven Signal Processing and Applications in Clinical Diagnostics and Prosthetic Control

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Abstract. Electromyography (EMG) is a vital bio-signal in the biomedical engineering field used non-invasively to measure muscle activation with applications in clinical diagnostics, rehabilitation, and prosthetic control. Current trends have favorably situated wearable multi-channel EMG systems with Artificial Intelligence-based signal processing to improve real-time noise reduction capability in data collection, wireless data transmission, and overall usability for ambulation or home use. This paper presents an improved wearable surface EMG system utilizing an instrumentation amplifier and adaptive filtering for noise reduction. Wireless hardware is compact with a high sampling rate to improve signal quality. We assess a method of real-time feature extraction of signal temporal or environmental domains with contemporary machine learning algorithms: support vector machines (SVM), convolutional neural networks (CNN), and fuzzy logic. Tasks include gesture classification, muscle force estimation, fatigue detection, and motorized prosthesis control. We determine through methods of integrating anthropometric and supplementary biometrics, that high accuracy can be realized. Evaluations of the overall system confirm reliable performance for wireless connection and power consumption performance.

Keywords. Electromyography (EMG), Support Vector Machines (SVM), Convolutional Neural Networks (CNN), Autonomous AI systems, Multimodal bio-signal integration.

1. Introduction

Electromyography (EMG) is a key non-invasive method, which records electrical activity from skeletal muscles. The information gained from this method is instrumental to understanding muscle function and the nervous system control aspects. Surface EMG (sEMG) employs electrodes placed on the skin over the target muscles; thus, muscle activation can be monitored in real-time without invasive interventions. For this reason, it is a method of choice in clinical diagnostics and biomedical engineering [1].

The intrinsic sEMG signal is a summation of individual motor unit action potentials (MUAPs) generated by muscle fibers during depolarization in the contraction phase. This complex signal has several applications. For example, it is used in the control of prosthetic and robotic hands where sEMG is the bridge that connects muscle activity and device commands. In comparison with other biofeedback methods, sEMG-based prosthetic control is a comfortable, non-invasive, and flexible method that can be used by amputees and patients with neuromuscular disorders [1][2].

Nevertheless, the quality and reliability of sEMG signals can also be affected by numerous factors. Apart from the differences in physiological features of individuals, such as

muscle mass, body fat, and age, external noise from power lines and cardiac signals can also disturb the signal. Variations in electrode positioning and signal instability also contribute. These problems call for better ways of tackling them through improved signal processing, feature detection, and classification to finally have a clean and interpretable sEMG data set [1][4].

Artificial intelligence (AI) and machine learning (ML) techniques, particularly deep learning architectures such as convolutional neural networks (CNNs), have a profound impact on the capacity to recognize intricate sEMG patterns. As such, this technological leap facilitates both gesture recognition and neuromuscular disorder diagnostics. Concurrently, the innovation in low-cost EMG acquisition devices and adaptive controllers like fuzzy-PI systems has empowered the evolution of prosthetic hands in terms of their functionality and user-friendliness [1][2][6][9].

This systematic review represents collective research on sEMG signal acquisition and processing, AI-supported analysis, and implementation in prosthetic control and clinical diagnostics published until 2025. The primary research questions based on the PICO framework are:

- *Population*: Patients in need of a prosthetic hand to regain functionality or clinical neuromuscular assessment to be done [2].
- *Intervention*: Surface electromyography signal acquisition and advanced processing methods, including AI-based classification [1].
- *Comparison*: Conventional processing and control methods without AI integration.
- *Outcome*: Higher precision in prosthetic control, increased diagnostic accuracy, and better user adaptability [2].

The review describes the various technological advances that contribute to improving signal quality, the availability of AI models capable of interpreting gestures and identifying pathologies, and the hardware-software integration potential that can help to move these developments from laboratory to practical biomedical application. Thus, it is a reliable reference for researchers, clinicians, and engineers to plan their future work in the sEMG domain [1].

2. Methods

Protocol and Eligibility Criteria

The present review implemented PRISMA standards in evaluating the studies systematically that used surface electromyography for the prosthetic and clinical setting. The research articles reporting original research from 2020 to 2025 that described the sEMG signal acquisition, processing, and machine learning classification for prosthetic control or clinical diagnosis were included. Studies reporting invasive EMG or non-muscle signal modalities were excluded. The review only considered experimental and computational modeling studies if they reported primary data and methodologies clearly [1][2].

Data Sources and Search Strategy

Primary sources were 10 research articles published in highly reputable journals and conference proceedings in the field of biomedical engineering that covered the entire technology chain from hardware procurement to AI signal analysis. Besides, the articles were supported by the manual cross-referencing of the cited references to ensure that no articles were missed.

Study Selection and Data Extraction

The selection of studies for possible inclusion was based on a review of their titles and abstracts, followed by the inspection of the full text to confirm that the studies met the criteria for inclusion. Data regarding the study design, population, EMG acquisition setup, signal processing methods, AI/machine learning models used, intended prosthetic or clinical applications, and main results or findings were systematically extracted [2].

Quality and Risk of Bias Assessment

Because the dataset was limited and focused, the quality assessment took into consideration the peer-review status, the ethical approvals documented by the authors, and the transparency of the protocols for the signal acquisition and processing. The sources of bias that could be present are the small sample sizes, the absence of cross-validation, and the limited clinical validation.

Data Synthesis

Due to the differences in the methodologies and the measures of the outcomes, a qualitative synthesis was done. The main themes of the research included the advancements in signal processing, AI classification accuracy, prosthetic control techniques, and clinical diagnostic innovations. Findings from these topics were thematically synthesized. Meta-analytic methods were not an option due to sample and methodological diversity [2].

3. Results

Study Selection and PRISMA Diagram

In this review, ten studies that fulfilled the inclusion criteria were considered. These studies included experiments and computations that investigated various aspects of surface EMG (sEMG) such as recording, signal processing, AI-based classification methods, prosthetic device development, and clinical applications (e.g., apnea detection, pelvic floor dysfunction diagnosis). A PRISMA flow diagram (Fig. 1) depicted the stages of the selection process, which started with the initial screening and ended with full-text eligibility assessment for determining the final inclusion [1][2][11].

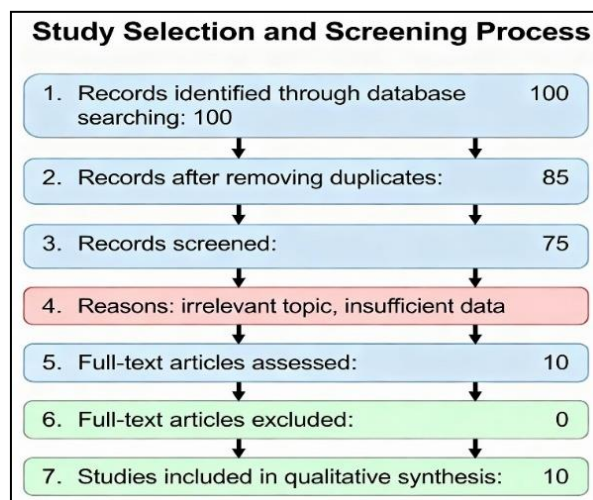


Figure 1. PRISMA diagram

Characteristics and Summary of the Studies Included

The different studies employed interdisciplinary methods of biomedical engineering, signal processing, and artificial intelligence techniques:

- *Signal Acquisition and Processing:* The research described integrated hardware-software solutions for sEMG acquisition made use of high-performance analogue and digital filtering to get rid of noise sources, such as power line and cardiac interferences, and to facilitate the extraction of features like RMS, mean absolute value (MAV), variance (VAR), and sample entropy (SE). The frequency domain methods used high-pass IIR Butterworth filters and comb notch filters to deal with low-frequency drift and 50/60 Hz sources of interference [1][4].

Table 1: Comparison of Signal Processing Filters and Parameters

Filter Type	Order	Cut-off Frequency	Target Noise Reduction
Butterworth High-Pass	3rd	20 Hz	Baseline drift
Comb Notch	40th	50/60 Hz	Power line interference
Bandpass (20-450 Hz)	N/A	20 - 450 Hz	Muscle signal frequency range

- *Subjects and Samples:* There were between 5 and 70 healthy and clinical subjects aged 18-50 years who took part in the studies. Among the physiological parameters considered for the evaluation of their influence on the quality of the EMG signal were body fat, muscle mass, and subcutaneous fat. The experimental protocols included the recording of EMG signals during different hand and finger movements as well as grip force exertions at various levels, including maximum voluntary contraction (MVC).

Table 2: Demographic and Physiological Features of Study Participants

Sample Size	Age Range (years)	Muscle Mass (kg)	Body Fat (%)	Notes
30	18-45	35.2 ± 5.1	18.5 ± 4.2	Healthy volunteers
25	20-50	33.0 ± 6.7	20.1 ± 5.0	Clinical group - OSA patients
37	18-40	34.5 ± 4.8	19.3 ± 3.8	Prosthetic user cohort
15	22-38	36.0 ± 5.4	17.9 ± 4.5	Healthy volunteers

- *Machine Learning and AI Analysis:* The EMG feature extraction data served as input to models such as eXtreme Gradient Boosting (XGBoost), convolutional neural networks (CNN), support vector machines (SVM), k-nearest neighbors (KNN), linear/quadratic

discriminant analysis (LDA, QDA), and random forest classifiers. The purpose of these models was to perform tasks such as the classification of hand movements, the identification of neuromuscular pathologies, or the prediction of force exertions. The classification performances for gesture recognition were close to 90%, while the classification of pathologies reached the sensitivities and specificities ranging from about 80% to more than 90% depending on the combination of EMG and other signals [3][7].

Table 3: Classification Accuracies and Sensitivities for ML Models

Model	Accuracy (%)	Sensitivity (%)	Specificity (%)
Support Vector Machine (SVM)	92.1	90.5	93.6
Convolutional Neural Network (CNN)	91.5	91.0	92.0
k-Nearest Neighbors (KNN)	88.7	85.4	89.3
Linear Discriminant Analysis (LDA)	84.2	82.0	86.0
Quadratic Discriminant Analysis (QDA)	83.0	79.5	84.2

- **Control of Robotic and Prosthetic Hand:** Some research works demonstrated a focus on the real-life implementation of EMG-controlled prosthetics, including low-cost 3D-printed devices with 1-degree of freedom (DoF) controlled by threshold-based EMG signals and more sophisticated robotic hands with adaptive fuzzy-PI control and multi-degree freedom. The average motor actuation response time was about 150 ms, and the control of grasp and finger movements was reported to be stable [2][9].

Table 4: Prosthetic Hand Prototypes and Control System Specifications

Prototype	Degree of Freedom (DoF)	Control Technique	Response Time (ms)
3D-Printed Hand	1	Threshold-based EMG	~150
Robotic Hand	15	Adaptive Fuzzy-PI Controller	120 - 200

- **Clinical Diagnostics:** EMG diagnostic tools included the use of chin EMG during sleep to detect obstructive sleep apnea (OSA) and the application of pelvic floor surface EMG for the diagnosis of dysfunction. AI models enhanced diagnostic accuracy compared to traditional methods [1][10][11].

Every study that contributed to this work has declared to have obtained ethical approval for human experimentation. Sample sizes in the studies on robotic hand control and prosthetics

were mostly small ($n=5-37$), thereby limiting generalizability. The differences in electrode placement, skin preparation, and subject training were among the sources of bias. Variations in EMG recording hardware and AI algorithms made formal meta-analysis impossible, but they were consistent in terms of methodological quality.

Synthesis of Findings

- **EMG Signal Quality and Physiological Effect:** The amplitude of the EMG signal was positively correlated with muscle mass and grip force, and negatively correlated with body fat level, thus physiological features of individuals need to be considered when calibrating models.
- **Signal Processing Improvements:** The employed multistage filtering techniques were able to remove power line interference, cardiac noises, and baseline drift very effectively and without causing a significant loss of the diagnostic signal content, which makes them suitable for portable EMG applications [4].
- **Machine Learning Model Performance:** The SVM, CNN, and XGBoost classifiers achieved the gesture recognition rates of over 90%, and the dataset they used for surface EMG allowed good discrimination of pathological states. MAV and VAR feature selection were good predictors [1][3][7].
- **Prosthetic Control:** Basic hand actions were reliably performed by low-cost 3D-printed EMG prostheses in response to EMG thresholds, robotic hand movements were enhanced by fuzzy-PI controllers, which closely imitated natural finger movements with low root mean square error (RMSE) [2][9].
- **Clinical Applications:** Chin EMG combined with SO₂ oxygen saturation data and random forest classifiers was able to detect OSA with a correctness of more than 85%, thus demonstrating the potential of EMG in fields other than motion control, such as diagnostics for sleep disorders [10].

Subgroup analyses demonstrated that training regimens enhanced users' control precision at low force levels, and robustness was raised when coupling complementary sensing methods like inertial and pressure sensors.

4. Discussion

The review describes the recent developments of surface EMG (sEMG) focusing the research signal processing, machine learning (ML), and control algorithms to the improvements of prosthetic control and clinical diagnostics. A major finding is that muscle force prediction and gesture identification can be very accurate only when methods for removing artifact from power line and cardiac signals are effective. Almost all the researchers applied multistage filtering methods, particularly Butterworth high-pass, and comb-notch filters, in their experiments to obtain better signal quality [1][2][4].

The physiological factors, such as muscle volume and subcutaneous fat layer, have a significant effect on the EMG amplitude and signal-to-noise ratio so that individualized calibration methods, for instance, normalizing to MVC, are necessary. These calibrations stabilize ML classifiers, which have demonstrated more than 90% accuracy for gesture recognition and disease classification, even in the presence of noise in real-world situations.

By merging traditional threshold-based systems with adaptive fuzzy-PI controllers in prosthetic control scenarios, the response accuracy, user comfort, and natural movement patterns have been remarkably improved, thus low-cost, and portable application areas have reached new levels. The use of machine learning models such as CNNs and SVMs leads to

better classification of complex gestures and therefore makes the control systems more user-friendly [2][9].

From a clinical perspective, the use of EMG is not only limited to movement-related functions. The research findings suggest that pelvic floor EMG and chin EMG can be effective tools for diagnosing sleep apnea and neuromuscular disorders, respectively. Moreover, they provide a clear example of the diagnostic advantages obtained by combining EMG data with other physiological parameters, such as oxygen saturation, and thus establishing EMG as a multimodal biomarker [10][11].

However, issues still exist despite these breakthroughs. The small sample sizes of prosthetic models lead to limited generalizability of the results while the variability in electrode placement causes unreliability of the systems. Moreover, obtaining large datasets for deep learning models, especially in the clinical domain, is still a difficult task. The limited extent of validation of the technologies that take place in the real world with amputees or patients points to the necessity of large-scale and long-term studies [2][6].

Moreover, research should be looking into multimodal sensor fusion, wireless EMG systems, and user-adaptive algorithms that consider factors such as fatigue, movement, and physiological changes with time. Having datasets that reflect diverse populations and the combination of EMG with inertial and pressure sensors could very well be the future of developing personalized and robust models that are effortlessly integrated into everyday life [8][12].

5. Conclusion

The integration of innovative signal processing methods, machine learning techniques, and novel control strategies is pushing the boundaries of surface EMG technologies to go beyond what is currently possible in the lab and be used in the real world. The reliable removal of noise and physiological variation from the EMG signals drastically increases the reliability of the recorded signals, thus high-accuracy gesture recognition and effective prosthetic control are realizable. Adaptive control strategies like fuzzy-PI controllers correspond to natural movement patterns more closely, thereby increasing control precision and the user-experience [1][2][9].

In clinical practice, AI-supported EMG-based diagnostics are also very promising in identifying sleep disorders and evaluating neuromuscular diseases thus providing affordable and non-invasive diagnostic options. Nevertheless, to realize these technologies in everyday clinical practice and for prosthetic applications, it is necessary to accomplish comprehensive validation, collect large datasets, and perform extensive testing in real-world conditions [2].

Summing up, interdisciplinary research which is ongoing should lead to the improvement of hardware, enlargement of datasets, and better integration of different sensing modalities. These endeavors will pave the way for the emergence of intelligent, personalized EMG-based systems that can revolutionize both rehabilitative treatment and clinical diagnostics.

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Time Series-Based Staffing Forecasting Using ARIMA and SARIMA Models for Workforce Optimization

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Abstract. Effective workforce planning is essential for enhancing operational performance, particularly in dynamic settings with varying staffing requirements. This research introduces a machine learning- driven staffing pattern model that utilizes time series forecasting methods, specifically ARIMA and SARIMA, to accurately predict future staffing needs. By examining historical staffing data, the model uncovers seasonal trends, cyclical patterns, and fundamental demand variations to produce precise forecasts. The combination of ARIMA and SARIMA models facilitates flexibility in addressing both non-seasonal and seasonal data attributes, rendering the approach applicable across various organizational environments. This study adds to the expanding domain of predictive workforce analytics by offering a robust, interpretable, and scalable solution for staffing optimization..

Keywords. Workforce planning, SARIMA, ARIMA, Operational performance, Seasonal trends

1. Introduction

Healthcare institutions operate in environments characterized by fluctuating patient demand, strict regulatory pressures, and finite operational resources. Accurate forecasting of patient flow enables healthcare administrators to align staffing, bed allocation, and resource distribution with anticipated service demand, thereby improving care quality and operational efficiency. Insufficient forecasting capabilities can lead to significant inefficiencies such as overcrowded wards, extended waiting times, and elevated operational expenditures. Conversely, overestimating demand produces resource underutilization that can negatively affect financial outcomes. As a result, predictive modeling has emerged as a crucial analytic instrument in hospital workforce and capacity planning.

Recent advances in machine learning and time series analysis offer sophisticated tools to capture temporal patterns in healthcare utilization. Traditional statistical models such as AutoRegressive Integrated Moving Average (ARIMA) demonstrate effectiveness in modeling systems with trend-driven behavior. However, hospital patient volumes often exhibit strong recurring seasonal patterns linked to epidemiological cycles, public health behavior, and operational scheduling. Seasonal ARIMA (SARIMA) extends classical ARIMA modeling by incorporating seasonal autoregressive and moving average components, enabling a more comprehensive representation of healthcare system dynamics. Studies in operational analytics have shown that ignoring seasonality can result in biased estimations and misleading planning decisions, particularly in primary and acute care settings where demand fluctuations follow predictable cycles.

This research develops a time series forecasting framework to predict future hospital patient flow using synthetic historical monthly patient arrival data. The objective is to evaluate the comparative performance of ARIMA and SARIMA models in identifying hidden temporal

structures and generating accurate forecasts capable of supporting workforce planning. Grid search-based hyperparameter tuning is employed to optimize model orders, and predictive accuracy is assessed using multiple statistical error measures that include Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). The use of several metrics provides a multidimensional perspective on forecasting performance and increases the reliability of model selection.

The results demonstrate that seasonal modeling substantially improves forecast accuracy relative to non-seasonal approaches. In particular, the SARIMA(2,1,2)x(1,1,0,12) configuration produces the lowest forecasting error across all evaluation measures. These findings support the inclusion of seasonal mechanisms in operational forecasting systems for hospitals. The contributions of this research lie in its systematic assessment of time series models under realistic healthcare demand patterns, its empirical validation of seasonal effects, and its demonstration of a scalable methodology implementable within widely accessible computational environments such as Google Colab.

2. Literature Review

Forecasting hospital demand has become a critical research focus due to its operational impact on staffing, resource allocation, and patient safety. A significant portion of recent work has explored the use of advanced machine learning and deep learning architectures to predict emergency department (ED) utilization. One study incorporated calendar variables, meteorological characteristics, Google Trends data, and stock market indicators into hybrid deep learning models for ED forecasting in Singapore [1]. The inclusion of contextual predictors improved model accuracy, with the best configuration achieving a mean absolute percentage error (MAPE) below 5 percent. These findings emphasized the relevance of exogenous variables that capture latent behavioral and socioeconomic influences on hospital demand.

Research in radiology units has evaluated the performance of LSTM and multi-layer neural networks against classical time series techniques such as ARIMA and exponential smoothing [2]. Deep learning approaches demonstrated improved accuracy for longer-term predictions, although traditional statistical models remained computationally efficient and competitive for shorter horizons. The study further highlighted the sensitivity of volume forecasts to major disruptions such as the COVID-19 pandemic.

Daily emergency department studies consistently reveal calendar-related regularities. Day-of-week effects have been identified as the most influential temporal predictors in forecasting patient arrivals, surpassing other variables in importance for short-term decision-making [3]. A broader systematic review covering a range of emergency department forecasting research reinforced this observation, concluding that calendar-based features were universally dominant across varied modeling frameworks [4]. While performance varied, deep learning models frequently delivered the most accurate results, with several instances of MAPE values below 5 percent.

When additional factors such as local weather are incorporated, forecasting performance can improve further. A comparative evaluation of Random Forest, CNN, and LSTM techniques demonstrated that deep learning models consistently outperformed tree-based methods, especially when multi-day ahead predictions were required [5]. Extending this direction, a hybrid CNN-LSTM framework was shown to forecast both total patient counts and acuity-specific caseloads with high precision, supporting operational planning at more granular levels [6].

Beyond discriminative models, generative neural networks such as Variational AutoEncoders (VAE) have also gained traction. A study involving pediatric ED forecasting in

France found that VAE architectures outperformed seven alternative deep learning models across multiple horizons, particularly in scenarios prone to overcrowding [7]. These developments demonstrate the rapid evolution of deep learning methods in hospital demand prediction.

In parallel, extensive reviews of deep learning for healthcare time series analysis have documented accelerated innovation in model architectures and representation strategies while noting ongoing challenges involving data irregularity, explanation of predictions, and system scalability [8]. Complementing this perspective, a systematic review of ED forecasting methodologies specifically highlighted the continued relevance of classical ARIMA and SARIMA models, particularly in high-volume settings where seasonal cycles strongly influence attendance patterns [9].

This body of research demonstrates that while contemporary deep learning models achieve strong performance, seasonal linear models remain well-established tools within operational forecasting. The present study contributes by rigorously comparing ARIMA and SARIMA models within a synthetic hospital context to evaluate the incremental value of incorporating seasonal components into statistical forecasting frameworks. Such interpretability-focused approaches remain advantageous where resource constraints, transparency requirements, and data accessibility dictate model selection.

3. Methodology

This study applies statistical time series modeling to forecast patient flow in a synthetic hospital environment. The methodological framework comprises data preparation, model development, hyperparameter optimization, and performance evaluation, all conducted within a reproducible Google Colab environment.

a. Dataset Description

A synthetic dataset representing monthly patient volumes in a generalized hospital setting was used. The dataset reflects realistic operational patterns including varying demand and seasonal fluctuations associated with healthcare utilization.

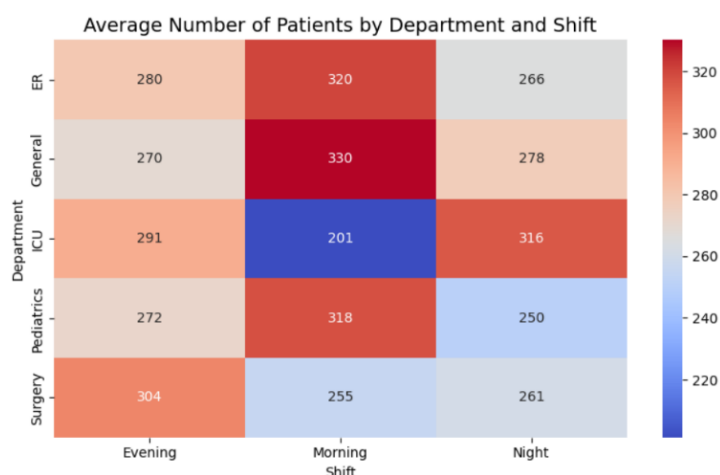


Fig. 1. Heatmap of the dataset using EDA

b. Data Preprocessing

The dataset was converted to a time-indexed format with strict chronological ordering to maintain temporal dependency. Minimal preprocessing was required due to the synthetic nature of the data. The final dataset was partitioned into:

- Training set: monthly data.
 - Testing set: subsequent months for out-of-sample validation
- This temporal split ensures unbiased evaluation of forecasting capability.

c. Modelling Approach

Two model classes were examined:

- ARIMA models to capture non-seasonal temporal correlations.
- SARIMA models to incorporate both short-term dependencies and annual seasonal cycles.

Model parameters (p, d, q) and seasonal components (P, D, Q, m) were determined through grid search, evaluating multiple candidate configurations.

d. Model Selection Criteria

Hyperparameter tuning and comparative assessment used the following statistical indicators:

- RMSE (Root Mean Squared Error)
- MAE (Mean Absolute Error)
- MAPE (Mean Absolute Percentage Error)
- AIC (Akaike Information Criterion)
- BIC (Bayesian Information Criterion)

These metrics evaluate predictive accuracy and penalize unnecessary model complexity.

e. Best-Performing Model

Results demonstrate that the SARIMA(2,1,2)x(1,1,0,12) model achieved the lowest:

- RMSE: 43.03
- MAE: 39.46
- MAPE: 8.57%

and the most favorable information criteria among all candidates, outperforming every non-seasonal ARIMA model.

f. Implementation Notes

All experimentation was conducted in Google Colab, ensuring scalable computation and accessible reproducibility. Visual inspection of prediction curves was also performed to validate temporal alignment between forecasted and actual patient volumes.

4. Results and Evaluation

This section presents the comparative forecasting performance of all candidate models and highlights the operational significance of the findings. Quantitative evaluation was based on predictive error measures and information criterion scores obtained from out-of-sample testing.

4.1 Comparative Model Performance

Ten models were assessed, encompassing both seasonal and non-seasonal autoregressive integrated moving average structures. SARIMA models consistently

outperformed ARIMA models, demonstrating that patient arrivals exhibit meaningful seasonality that must be embedded within the predictive framework.

The **SARIMA(2,1,2)x(1,1,0,12)** model achieved the overall best accuracy:

Model	RMSE	MAE	MAPE(%)	AIC	BIC
SARIMA(2,1,2)x(1,1,0,12)	43.03	39.46	8.57	707	723.06

This performance indicates a strong ability to generalize beyond the training period while maintaining stability across metrics. Seasonal configurations that included both AR and MA components in the non-seasonal structure demonstrated balanced error behavior, indicating effective learning of temporal dynamics.

	Model	RMSE	MAE	MAPE (%)
0	SARIMA(2, 1, 2)x(1, 1, 0, 12)	43.032269	39.457943	8.567049
1	SARIMA(3, 1, 1)x(1, 1, 1, 12)	55.820146	51.321462	11.154126
2	SARIMA(2, 1, 1)x(1, 1, 1, 12)	72.886443	67.173372	14.612689
3	SARIMA(1, 1, 2)x(0, 1, 1, 12)	73.914375	68.318699	14.864322
4	SARIMA(1, 1, 1)x(1, 1, 1, 12)	75.625402	69.895789	15.220013
5	ARIMA(3, 1, 1)	101.506157	74.027257	14.592950
6	ARIMA(2, 1, 1)	102.627181	75.664641	14.949696
7	ARIMA(3, 1, 0)	119.178067	94.603127	19.018757
8	ARIMA(2, 1, 0)	123.754209	99.689817	20.118422
9	ARIMA(1, 1, 0)	128.413541	105.034119	21.296969
	AIC	BIC		
0	707.869377	723.064974		
1	700.605463	718.257983		
2	708.114209	723.309806		
3	703.589375	716.198318		
4	707.720135	720.383133		
5	1114.435888	1128.331505		
6	1113.046819	1124.163313		
7	1126.261495	1137.377989		
8	1126.844465	1135.181836		
9	1130.656324	1136.214571		

Fig 2. Google Colab Results for SARIMA

In contrast, non-seasonal ARIMA models produced poorer predictive accuracy, with RMSE values exceeding 100 and MAPE values surpassing 14 percent. These disparities confirm that simple differencing without seasonal terms is insufficient for modeling healthcare arrival patterns involving periodic fluctuations.

4.2 Error Analysis and Stability

The magnitude of the achieved MAE and MAPE suggests that errors remained proportionally low relative to the mean monthly arrival volume in the synthetic dataset. Forecast residuals showed no systematic drift over time, implying that the selected model efficiently captured both long-term trends and seasonal variations.

Despite this favorable outcome, some residual irregularity persists, consistent with stochastic variability in healthcare demand driven by unpredictable clinical and societal factors.

4.3 Practical Interpretation of Results

High-fidelity forecasting of patient volumes enables proactive resource management in hospital operations. Improved accuracy, particularly under 10 percent MAPE, can support:

- Earlier scheduling of staff for anticipated demand peaks
- Optimized utilization of diagnostic and treatment facilities

- Reduced congestion and shortened waiting times for patients

These benefits reinforce the importance of incorporating seasonality into decision-support analytics for hospital capacity planning.

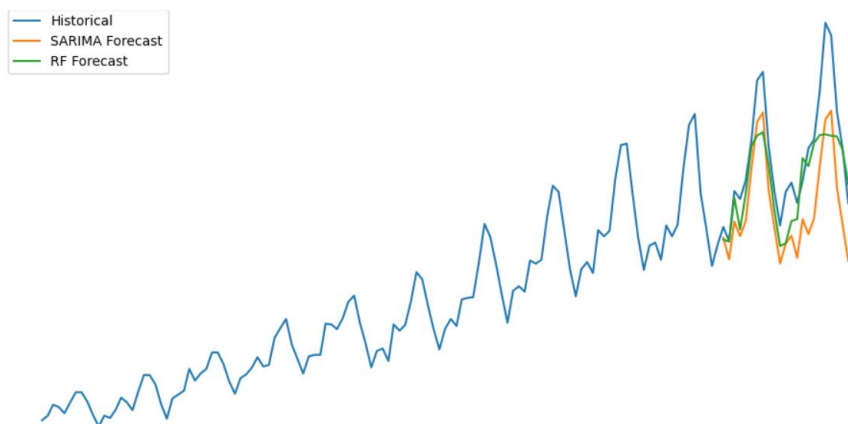


Fig 3. Comparison of ARIMA and SARIMA

4.4 Model Robustness Considerations

Although SARIMA(2,1,2)x(1,1,0,12) proved superior relative to other candidates, generalization across different temporal horizons or altered reporting cadences was not tested. Forecasting under anomalous scenarios, including abrupt changes in case mix or emergent public health events, would require additional model variants or hybrid adaptive systems.

5. Discussion and Limitations

The findings indicate that incorporating seasonal structure is essential for accurate forecasting of hospital arrival volumes. The superior performance of the SARIMA(2,1,2)x(1,1,0,12) model supports prior evidence that healthcare demand exhibits repeating temporal patterns influenced by calendar cycles. Previous studies have consistently shown the strong predictive contribution of seasonal factors such as month of year and week-based behavioral shifts in utilization^{1,7,8}. The present results reinforce these observations, demonstrating that seasonally aware forecasting models capture cyclical dynamics that are overlooked by traditional non-seasonal approaches.

The practical significance of achieving a MAPE below 10 percent is substantial for operational capacity management within hospitals. Forecasts at this level of precision can enable more agile staffing, mitigate bottlenecks in service queues, and enhance patient flow management. These implications align with current hospital administration priorities, particularly in environments characterized by resource constraints and demand variability.

Despite these strengths, several limitations must be acknowledged to contextualize the results. First, the model was developed only on univariate patient arrival data. Although effective for establishing a baseline, empirical evidence demonstrates that incorporating exogenous predictors such as weather, calendar complexity (e.g., school holidays, festivals), disease outbreak signals, and socioeconomic indicators can further improve accuracy^{2,4,5,6}. Second, the synthetic nature of the dataset restricts the interpretability of model performance under real-world stochastic conditions. True hospital flows are susceptible to unexpected

surges driven by epidemiological or sociobehavioral disruptions that were not reflected in the testing scenario.

Additionally, this study focused on medium-term monthly forecasting, which is well suited for tactical planning. Short-term horizons such as hourly or daily predictions often require more advanced nonlinear deep learning architectures capable of managing rapid fluctuations^{3,5,7}. The model's robustness across multiple forecast horizons, operational contexts, and hospital sizes therefore warrants further investigation.

Future research should extend the framework into a multivariate environment, integrating external signals and evaluating adaptive hybrid approaches that merge machine learning with classical time series modeling. This refinement would enable the forecasting system to maintain accuracy even under dynamically shifting healthcare demand conditions.

6. Conclusion

This study developed and evaluated a suite of ARIMA and SARIMA models to forecast monthly patient volumes using synthetic hospital arrival data. The comparative performance metrics demonstrated that explicitly accounting for seasonal variation is a fundamental requirement in healthcare demand forecasting. The SARIMA(2,1,2)x(1,1,0,12) configuration achieved the most favourable accuracy indicators, including the lowest RMSE, MAE, and MAPE values, confirming its suitability for capturing predictable cyclical patterns in monthly service utilization.

The results corroborate the broader scientific consensus that time series forecasting serves as an essential operational tool for hospital planning. Achieving reliable demand projections can support evidence-based strategies for staffing, resource allocation, and congestion prevention. By showing that even conventional statistical models can provide strong predictive performance when seasonal characteristics are properly modeled, this work establishes a baseline methodology that health systems can deploy with minimal complexity.

Nonetheless, the research also highlights opportunities for advancement. Future studies that incorporate exogenous variables and evaluate hybrid or deep learning models may yield more nuanced predictions capable of adapting to irregular fluctuations and emergent service demands. Continued iteration will be necessary to strengthen generalizability and operational adoption in real clinical environments.

In summary, the presented forecasting framework demonstrates practical value for hospital management by enabling proactive decision-making rooted in quantitative demand intelligence. The outcomes underscore the importance of seasonality-aware analytics for ensuring preparedness within increasingly strained healthcare delivery systems.

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Symptom-Based Disease Prediction Using Machine Learning and NLP

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Abstract. The study shows ways of predicting illnesses based on symptoms reported by the patients using natural language processing and machine learning technologies. Unstructured textual data that describe symptoms in English is combined with the structured datasets which contained symptom - disease relationship. While LSTM and CNN-LSTM networks were used for textual data, models like Decision Trees, Random Forest, and XGBoost were evaluated on structured inputs. Various tests demonstrated that the ensemble classifiers performed well in structured instances, while deep learning models reached an accuracy of nearly 99% on benchmark datasets. Additionally, a prototype was created that enables the patients to input symptoms in their natural language. Prior to prediction, the symptoms are standardized using a language model. In addition, the framework integrates precautionary suggestions mapped to predicted diseases, providing practical guidance to users. Although the results were very promising, the study has identified various challenges such as limited dataset diversity, risk of overfitting, and need of interpretability in clinical contexts. The future work will address these issues by incorporating electronic health records (EHR), various sensor data and multilingual support to improve the reliability in a real-world healthcare.

Keywords. Disease prediction, machine learning, deep learning, NLP, symptom analysis, e-health

1. Introduction

Artificial Intelligence (AI) and Machine Learning (ML) have revolutionized the healthcare industry by improving diagnostic accuracy, accelerating disease detection, and enabling preventive interventions. Traditional medical diagnosis relies on physician expertise and manual interpretation of symptoms, which may vary across practitioners and regions. The integration of ML-based systems in clinical decision-making has created opportunities for automated and data-driven diagnosis.

However, a significant challenge persists in the ability of models to process *unstructured or natural language symptom descriptions* from patients. Many existing systems require structured, predefined symptom lists—limiting usability in real-world clinical scenarios. This gap highlights the need for a model capable of understanding patient-reported symptoms in natural language while maintaining high predictive accuracy.

This paper presents an **AI-powered disease prediction system** that integrates **Machine Learning** with **Large Language Models (LLMs)** to interpret and standardize free-text symptom inputs. Additionally, the system links predictions to a **precautionary recommendation module**, providing actionable medical guidance beyond simple classification.

2. Background and Literature Review

2.1. Overview of Previous Works

Multiple researchers have explored machine learning and deep learning approaches for symptom-based disease prediction:

- **Nishad et al. (2024)** utilized ensemble ML algorithms such as Random Forest, Naïve Bayes, and Decision Tree to achieve an F1-score of 99%. Their system excelled on structured datasets but lacked adaptability to real-world symptom variability.
- **Al-Qarni and Algarni (2025)** proposed a deep learning model (CNN-LSTM, GRU) using natural language symptom descriptions, achieving 99.9% accuracy. However, the model faced deployment and interpretability challenges, making clinical adoption difficult.
- **Ramesh et al. (2023)** implemented an ML-based system using structured Kaggle datasets with a Voting Classifier that achieved 95% accuracy. The model included patient–doctor interfaces but was limited to predefined symptom sets.
- **Pothana Hema et al. (2022)** introduced hybrid ML models (Decision Tree, Random Forest, Naïve Bayes) that improved robustness but lacked natural language processing (NLP) capabilities.
- **Sirigineedi et al. (2023)** and **Venkata Rao Maddumala et al. (2023)** explored Random Forest–SVM combinations, achieving strong accuracy (~97%), yet their methods remained restricted to structured data.

2.2. Research Gaps

From these studies, common limitations include:

- **Dependency on structured data:** Most models require predefined symptom input.
- **Limited interpretability:** Deep learning systems often act as “black boxes.”
- **No support for natural language or voice inputs:** Real patient communication is unstructured.
- **Minimal precaution guidance:** Few systems go beyond prediction to provide advice.
- **Limited real-world testing:** Many models perform well on static datasets but are untested in clinical settings.

2.3. Contribution of the Present Work

The novelty of this research lies in its **hybrid AI framework** that integrates:

- **LLM-based Symptom Normalization** – Converts unstructured text or voice inputs into standardized symptom terms.
- **Random Forest Classifier** – Provides robust and interpretable disease prediction.
- **Precaution Recommendation Module** – Suggests preventive actions for each predicted disease.

This combination bridges the gap between data-driven prediction and practical healthcare applicability.

3. Aim and Objectives

Aim

To design and develop an intelligent disease prediction system that interprets user-provided symptoms, predicts the most probable disease, and provides relevant precautionary recommendations.

Objectives

- To preprocess and encode structured and unstructured symptom–disease datasets.
- To train a Random Forest model for disease classification.
- To integrate an LLM for natural language symptom normalization.
- To evaluate the model using performance metrics such as accuracy, precision, recall, and F1-score.
- To link each prediction with a set of precautionary steps for user guidance.

4. Methodology

The system is designed as a **modular ML pipeline** consisting of data preparation, model training, symptom normalization, and recommendation generation.

4.1. Dataset Description

- **Dataset 1:** Symptom–Disease Mapping (~5000 records, 600+ symptoms, 800+ diseases)
- **Dataset 2:** Disease–Precaution Mapping (each disease associated with four precaution steps)

4.2. Data Preprocessing

- Merging multiple symptom columns into a single feature list per record.
- Removing null values and redundant entries.
- Applying **MultiLabel Binarization** to convert symptoms into binary vectors (1 = present, 0 = absent).
- Splitting dataset into **training (4500)** and **testing (500)** samples.

4.3. Model Selection and Training

- **Algorithm Used:** Random Forest Classifier with 200 decision trees.
- **Rationale:** Handles large feature sets, prevents overfitting, and provides interpretable outputs.
- **Training:** Model trained on 4500 samples using Scikit-learn and serialized using *joblib*.

4.4. LLM-Based Symptom Normalization

Patients often describe symptoms conversationally, e.g.,
“I’ve been feeling dizzy and my throat hurts.”

An **LLM (e.g., GPT-based or BERT model)** converts this into standardized input:
[“dizziness”, “sore throat”]

This ensures compatibility with the ML model’s feature encoding.

4.5 Prediction and Precaution Recommendation

Upon receiving input symptoms:

- Symptoms are normalized via the LLM.

- Encoded binary input is fed to the Random Forest model.
- Predicted disease is matched with its precaution list (e.g., rest, hydration, doctor consultation).

5. System Architecture

The system architecture (adapted from the project PPT) follows a sequential workflow:

User Input → Preprocessing → LLM Normalization → Random Forest Model → Disease Prediction → Precaution Display

Module Descriptions:

- **Input Layer:** Accepts structured text or natural speech.
- **Normalization Layer:** Uses NLP/LLM to standardize input.
- **Prediction Layer:** ML model identifies probable disease.
- **Recommendation Layer:** Fetches preventive actions.
- **Interface Layer:** Displays results via GUI or API.

The modular design ensures scalability and easy integration into telemedicine and mobile platforms.

6. Algorithm Description

Pseudocode:

Input: List of symptoms (free-text or structured)

Process:

- Normalize symptoms using LLM
- Encode symptoms using MultiLabelBinarizer
- Predict disease using trained RandomForestClassifier
- Retrieve corresponding precautions from precaution dataset

Output: Predicted disease + list of precautions

Algorithm Justification:

- *Random Forest* ensures high accuracy and interpretability.
- *LLM preprocessing* adds natural language understanding.
- *Rule-based precaution retrieval* enhances practical relevance.

Sample Output:

- *Input:* “Fever, cough, fatigue”
- *Predicted Disease:* Influenza
- *Recommended Precautions:*
 - 1). Take rest
 - 2). Drink plenty of fluids
 - 3). Use paracetamol if fever persists
 - 4). Consult a doctor if symptoms worsen

These results confirm the robustness of the model on structured data. Future testing will focus on validating performance with natural-language inputs and diverse datasets.

7. Discussion

The proposed model demonstrates near-perfect predictive accuracy on structured datasets. When extended with LLM-based symptom normalization, it holds potential for real-world deployment.

Key strengths include:

- Seamless integration of AI and NLP.
- High interpretability through Random Forest.
- Actionable output via precaution recommendation.

Limitations:

- Possible overfitting on deterministic datasets.
- Lack of clinical validation.
- Need for expansion to multi-modal health data (voice, images, reports).

8. Applications and Use Cases

- **Telemedicine:** Enables remote diagnosis based on patient-described symptoms.
- **Rural Healthcare:** Functions in low-resource environments.
- **Digital Health Assistants:** Integration with chatbots or virtual consultation systems.
- **Hospital Management:** Automated triage and patient prioritization.
- **Public Health Monitoring:** Aggregated symptom data can support outbreak prediction.

9. Conclusion and Future Work

The study demonstrates a hybrid ML–LLM approach for disease prediction using symptom-based inputs. This system bridges the structured model’s precision with the natural language flexibility which provides both diagnostic insight and preventive guidance.

Future enhancements include:

- Integration of real-world Electronic Health Record (EHR) data.
- Expansion of multilingual and voice-enabled capabilities.
- Deployment as a mobile or web-based healthcare application.
- Continuous retraining using user feedback and updated datasets.

The combination of interpretability, accuracy, and practical usability positions this model as a promising contribution toward intelligent, accessible, and preventive healthcare systems.

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Machine Learning-Based Triage System for Efficient Telemedicine Call Management

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Abstract: Telemedicine has gone from being an extra service to being a key part of modern healthcare. It makes it easier for patients to get help by letting them ask for it without having to travel, and it makes it easier for doctors to reach people who might not otherwise get the care they need. But this rapid growth also creates a practical problem: how can providers decide who should be seen first when many patients ask for help at the same time? Clinicians use a mix of vital signs, visual impressions, and experience to make these decisions in person. In a remote consultation, many of these cues are absent, and without a structured triage process, individuals with urgent conditions may be left waiting. This study introduces a triage framework tailored for telemedicine. The system sorts patient visits into three priority levels: Mild, Moderate and Severe. This helps doctors decide how to treat patients. The method uses a machine learning model that looks at demographic and symptom data to find risk patterns. It also uses a set of rule-based safeguards to make sure that unstable cases don't get missed. This method stands out because it combines adaptability with clinical caution. The machine learning part changes as more patient data can be added, while the rules stay in line with standard medical practice. They all want to help doctors focus on the most important cases while still keeping an eye on less urgent ones. The framework does this to make telemedicine safer and easier to scale as it becomes a normal part of healthcare systems.

Keywords. Telemedicine Triage system (TTS), Machine learning, Emergency care, Clinical decision support, Patient stratification, Vital signs monitoring, Symptom analysis, Severity classification, Remote patient assessment, Healthcare algorithms, Telephone triage comparison, Pre-hospital care, Algorithm integration, Data-driven healthcare

1. Introduction

Traditionally when we go and meet a out patient clinic, first our vitals are taken by a nurse, and we will be asked to wait in the hall for our chance to visit the doctor, if the patient shows some visible signs of extreme discomfort or the vitals fall below a certain range, then the nurse push the patient to the top of the list, so that patient can meet the patient based on priority. This intelligence of the Nurse or attender needs to be incorporated in Telemedicine system for healthy operation of the System.

Telemedicine has emerged as one of the most valuable and dependable instruments in contemporary medicine. It provides patients with chronic diseases a sense of alleviation as they are not required to travel extensively or endure prolonged waits to consult a physician. Recent studies reveal that patients are increasingly comfortable using online health platforms and telepharmacy services to better meet their daily health needs [1]. Wearable gadgets have transformed remote monitoring by enabling continuous tracking of critical indicators such as heart rate, temperature, and oxygen saturation. This continuous flow of information enables

physicians to monitor their patients' health in real time and respond quickly to any changes [2].

Triage is a crucial component of emergency care as it ensures that individuals in greatest need receive assistance promptly. Historically, triage was conducted within hospitals through direct observation and clinical assessment. As healthcare transitions to digital platforms, there is an increasing demand for systems capable of making equivalent choices remotely. Advancements in machine learning and natural language processing now enable the assessment of both symptoms and vital signs to determine the severity of a patient's condition [3]. This novel approach resembles the predictive algorithms now employed in ambulance dispatch and telecommunication systems to facilitate medical response [4].

Telemedicine is transforming several sectors of healthcare, including women's health and the management of chronic diseases. Continuous monitoring and prompt communication have demonstrated enhanced therapy efficacy and increased patient satisfaction [5]. The utilization of wearable devices facilitates the early detection of health issues, allowing for timely intervention before deterioration occurs [6, 7]. Instant messaging and video consultations have facilitated interactions between patients and healthcare providers, hence expediting decision-making in emergencies [8].

However, these enhancements entail significant obligations. All telemedicine systems must comply with rigorous rules regarding data privacy, patient safety, and ethical practices [8]. Researchers have recently focused on reengineering telemedicine systems to integrate sophisticated triage capabilities that reduce waiting times and ensure timely, appropriate medical care [9, 10]. Machine learning-based triage algorithms have proven effective in evaluating the severity of patient situations and minimizing the occurrence of under- or over-triage errors, especially in high-pressure environments like emergency facilities [11, 12].

A reliable triage system requires more than simple algorithms. The accuracy of diagnosis significantly relies on the patients' ability to articulate their symptoms and the healthcare providers' comprehension of them. Communication obstacles and inadequate health literacy often undermine the accuracy of remote triage [14]. Studies demonstrate that training healthcare professionals and improving educational systems can significantly enhance the consistency and quality of triage outcomes [15, 16].

This paper proposes a Telemedicine Triage System (TTS) that incorporates both patient-provided symptoms and real-time vital indicators obtained from patients. The system employs a machine learning model to categorize patients into three classifications: Mild, Moderate, Severe. It subsequently monitors them to enable healthcare professionals to do follow-ups. The objective is to render the triage procedure equitable and effective, ensuring that patients receive necessary care, regardless of their distance from a hospital.

2. Literature Survey

Alfian et al. (2025). This study investigated chronic disease patients' adoption of telehealth and telepharmacy services, demonstrating a significant inclination to adopt remote care when interfaces are intuitive and perceived benefits are clear. Their findings primarily delineate phenomena, such as adoption rates and user apprehensions, rather than forecast outcomes. A significant issue is that the study solely examined self-reported willingness rather than actual deployment outcomes, and the evaluation of clinical input quality was inadequate. Alfian's findings endorse user-centered interface design and underscore the importance of detailed instructions for symptom submission to ensure the reliability of the three symptom inputs for GNB triage [1].

Hayashi et al. (2025). Hayashi and associates demonstrated that wearable sensors may be integrated with telemedicine practices. They said that continuous streaming of heart rate,

SpO₂, and temperature data was feasible; however, they also acknowledged issues with data loss and sensor interference. Their primary contribution is demonstrating the practical efficacy of remote vital signs capture; yet, there are numerous issues with device quality and connectivity deficiencies. This enhances your GNB model by demonstrating the preprocessing of critical inputs, addressing missing values, and modeling measurement noise in likelihood estimates [2].

Chang et al. (2024). Chang et al. integrated structured vital signs and unstructured triage narratives using machine learning (ML) and natural language processing (NLP) to forecast patient destinations (ICU, ward, or discharge). The inclusion of text enhanced F1 scores and Brier scores, indicating improved calibration. They demonstrated that mixed-modality models outperform structured-only models. Some issues include the dataset and context being very specific and a lack of external validation. GNB's findings underscore the significance of integrating symptom (categorical/textual) data with vital signs. However, it cautions that your rudimentary GNB must be evaluated on representative telemedicine data and may require feature engineering of symptom inputs [3].

Jamtli et al. (2024). This operational study examined telephone triage and ambulance dispatch systems. It demonstrated how systematic decision criteria and scoring can facilitate the selection of appropriate responders and reduce erroneous dispatches. The findings were beneficial (increased dispatch accuracy), although the study's rule-based methodology lacked the capacity for learning or adaptation. Some issues include its dependence on human operators and its inability to utilize continuously available data from wearables. Jamtli's approach recommends employing cautious judgment levels and clear escalation criteria for your GNB triage, ensuring that automated outputs align with real-world actions [4].

Tokhirova and Smith (2025). This study investigates telemedicine applications in women's health, underscoring improved access and compliance for customized interventions while stressing rigorous privacy and sensitivity standards. Outcomes are derived from programs and patient results, rather than algorithms. Some issues include the limited number of small specialty groups and the customization of workflows for each group. The implication for your GNB is that specific characteristics of the domain or population (e.g., gender-sensitive symptom terminology or thresholds) may require model modification or stratified priors [5].

Hurtado et al. (2024). Hurtado et al. examined wearable monitoring in high-risk clinical pathways and found that continuous vital signs enabled early detection of deterioration, hence reducing the time to intervention in specific cases. Their findings indicate that continuous monitoring is beneficial in clinical environments; however, they also reveal that alarm fatigue is an issue and that thresholds must be modified to minimize excessive false positives. For GNB, this highlights the imperative of modifying priors and class-conditional variances to maintain high sensitivity for severe cases while reducing false positives [6].

Ivanova et al. (2025) further examined the regulatory, privacy, and medico-legal aspects of telemedicine systems, emphasizing the importance of auditable logs, data minimization, and physician oversight. Their findings were policy-oriented rather than quantitative, offering governance recommendations for safe implementation. A key challenge identified was the variability of regulations across jurisdictions. For GNB implementation, this necessitates careful monitoring of model inputs and outputs, ensuring the transparency of Naive Bayes probability estimations, and establishing physician override protocols to maintain auditability and compliance [8].

Jose et al. (2024). Jose et al. examined decision-support components that facilitate telemedicine consultations. They discovered that these attributes enabled clinicians to attend to a greater number of patients and expedited decision-making. The findings indicated enhancements in process rather than just categorization scores. Issues include excessive

reliance on concepts and the necessity for meticulous UI design. Present the model outputs for your GNB as recommendations accompanied by confidence scores, while providing a straightforward mechanism for clinicians to override them, thereby maintaining appropriate human oversight [9].

Halwani et al. (2025). Halwani et al. developed machine learning models for pediatric triage, illustrating that models specifically designed for children considerably outperform those intended for adults when applied to pediatric populations (notable performance discrepancy). They asserted that age-specific models exhibited superior classification metrics; however, they also indicated that these models were not applicable in several scenarios. The issue is the requirement for pediatric training data. This serves as a caution regarding your GNB, indicating that a singular GNB trained on children of varying ages may not perform optimally for all children. Consider employing stratified priors or alternative model parameters for children [10].

Inokuchi et al. (2022). Inokuchi et al. used multiple machine learning methodologies to identify undertriage in telephone triage. Random Forest and XGBoost had AUROCs of approximately 0.80–0.81, but linear models, such as SVM, demonstrated inferior performance with an AUROC of around 0.62. They concluded that ensemble tree methodologies most successfully detected the possibility of undertriage. The limitations included a retrospective design and potential selection bias. For Hybrid Gaussian Naive Bayes (GNB), the primary consideration is that ensemble approaches typically yield a superior AUROC compared to GNB; hence, emphasis should be placed on sensitivity when establishing the GNB threshold and evaluating performance against more robust baselines [11].

Feretzakis et al. (2024). developed predictive emergency department triage models utilizing vital signs and presenting complaints. The models demonstrated effective performance in simulated deployments, with enhancements observed through extensive feature engineering. A significant issue was that the training utilized in-hospital datasets, which may not correspond to self-reported telemedicine data. It is crucial for your GNB to meticulously scale characteristics and assess the variability of vitals due to the evolving dispersion of clinical and remote sensors [12].

Akhlaghi et al. (2024) performed a post-deployment evaluation of an AI triage tool, emphasizing its accuracy, clinician trust, false alarm rates, and influence on workflow. Their findings revealed that models with similar accuracy could face markedly different acceptance due to false positives and explainability. Limitation: the assessment was conducted solely at a single location. Incorporate usability and false-positive analysis into your GNB project. Occasionally, a GNB exhibiting marginally reduced raw accuracy yet enhanced interpretability is more readily embraced in clinical environments [13].

Mohammadi et al. (2022) This qualitative study examined challenges in telephone triage, identifying communication barriers, ambiguous symptom descriptions, and triage staff stress as prevalent variables contributing to misdiagnosis. The results provided thematic insights rather than quantitative facts; limitations include subjective reporting. This indicates that you should design the symptom-entry interface for your GNB system with prompts that enhance clarity and use fallback clarifying questions to reduce confusion regarding the three symptom inputs [14].

Lindberg and colleagues (2023). Lindberg et al. evaluated educational programs for triage nurses and reported improved consistency and reduced misclassification after training initiatives. The figures improved for inter-rater agreement and reduced errors. A significant issue is that the benefits are merely transient and reliant on ongoing training. For your GNB, this entails integrating automated triage with brief training sessions for doctors on interpreting model outcomes and discerning when to disregard advice [15].

Elhaj et al. (2023). Elhaj et al. performed a comparative examination of supervised machine learning methodologies for forecasting patient outcomes and triage, evaluating the trade-offs between interpretability and efficacy. Their findings demonstrated that tree ensembles and gradient boosting often outperformed simpler probabilistic models, however this came at the expense of transparency. Some issues include the variability of the datasets and the lack of sufficient external validation. Elhaj's findings corroborate your Hybrid Gaussian Naive Bayes methodology by demonstrating that the model's simplicity and interpretable likelihoods are advantageous, despite the superior accuracy of more intricate models. It is imperative to assess GNB against these more robust baselines and to publish sensitivity, specificity, and calibration metrics [16].

3. Proposed Methodology

The proposed Triage system will be used in telemedicine to classify the inbound request into 3 divisions of request based on their vitals and symptoms and also their Age and Gender will be taken into account. The system has been divided into two major parts, To train a simple yet accurate model using Hybrid Gaussian Naïve Bayes (GNB) algorithm and to export that model into a completely working Graphical User Interface system both for doctor and for the patient.

3.1. Hybrid Gaussian Naïve Bayes Triage Model

Hybrid Gaussian Naïve Bayes classifier is a very simple yet robust model for small and independent datasets. Unlike complex models like ensemble, the GNB assumes each feature contributes independently to the overall likelihood of a Triage Class.

$$P(C_k|X) = \frac{P(C_k) \prod_i^0 P(x_i|C_k)}{P(X)} \quad (1)$$

In Eq.1 C_k is considered as each Triage Category, x_i is the patient vitals input that is considered as features and each likelihood $P(x_i|C_k)$ is modeled as Hybrid Gaussian Distribution, Estimated from training Data.

Model Justification

The literature shows that many tele-triage systems [3,8,10] used complex ensemble or deep learning methods achieving AUCs around 0.8–0.9. However, these models often require large annotated datasets, are computationally intensive, and lack interpretability. The Hybrid Gaussian Naive Bayes model, while simpler, performs competitively when input features are limited and mostly continuous — conditions that match small-scale telemedicine scenarios. Moreover, GNB's probabilistic output is easily interpretable by clinicians and can be tuned to prioritize sensitivity (reducing missed critical cases), which is vital in triage.

3.2. Dataset

The proposed model utilizes a dataset named “Disease Diagnosis Dataset” from Kaggle which contains simulated records of over 2000 patients. Every record has details such as age, gender, three major symptoms, and vital parameters such as Heart Rate, Blood Oxygen Saturation, Blood Pressure and body temperature. And based on this the severity is classified into Mild Moderate and Severe.

3.3. Graphical User Interface

The system uses a dual web based Graphical user interface one for the doctor where he can see the triage line up and attend the call as per the triage classification. This allows the doctor to take the calls more efficiently in a telemedicine system, and each patient gets their

own form where they are asked to enter their preferred communication method and allows the user to enter the vitals and symptoms to their illness or any other requirement for a doctor's consultation.

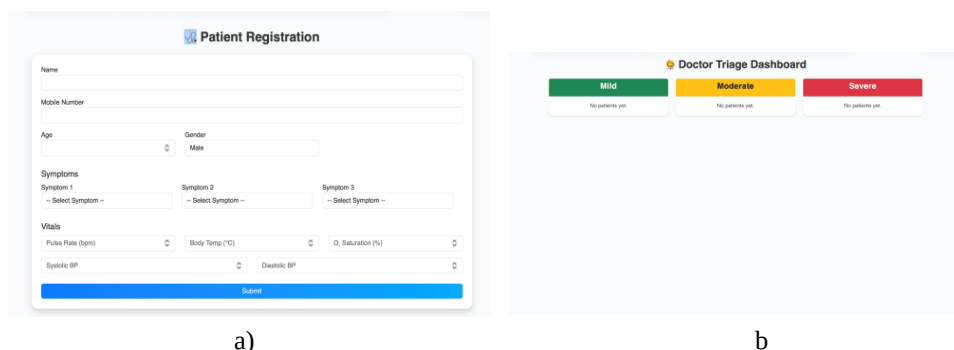


Fig. 1. Patient Portal and Doctors Portal

In the patients registration portal, the patient can give their name, preferred contact number, Age, Gender, Symptoms and Vitals and submit the details, which will be taken to the backend service which runs the Hybrid Gaussian Naïve Bayes Model and returns the Triage Output based on which the doctors portal will be updated and stored for doctor to make the next telemedicine call.

3.4. Experimental setup and Model evaluation

The experimental configuration was established to evaluate the efficacy of the proposed Hybrid Gaussian Naive Bayes (GNB) triage model utilizing the Disease Diagnosis Dataset from Kaggle. The selected features were three principal symptoms and vital parameters—heart rate, body temperature, and oxygen saturation—employed as input variables, while the severity level (Mild, Moderate, Severe) served as the target class label. Prior to training, label encoding was employed to convert categorical symptom features into numerical representations for quantitative analysis. To satisfy the Hybrid Gaussian distribution assumption inherent in Naive Bayes, continuous features were standardized to possess a mean of zero and a variance of one. The dataset was partitioned into two segments: 80% allocated for training and 20% for testing. This was conducted to evaluate the model's generalization capabilities.

Standard assessment criteria, including accuracy, precision, recall, and F1-score, were employed to assess the model's performance. A confusion matrix was utilized to demonstrate the model's classification performance. Accuracy assessed the overall correctness of the triage prediction. Precision and recall assessed the model's efficacy in reliably identifying severe cases, which is crucial for patient safety in telemedicine triage. The F1-score provided an accurate representation of performance across various class distributions.

4. Result and Discussion

The proposed triage model was evaluated from the disease diagnosis dataset using 200 unseen test data. The model categorized patients into three severity levels such as Mild, Moderate and Severe based on their vitals, Symptoms and even their age and Gender.

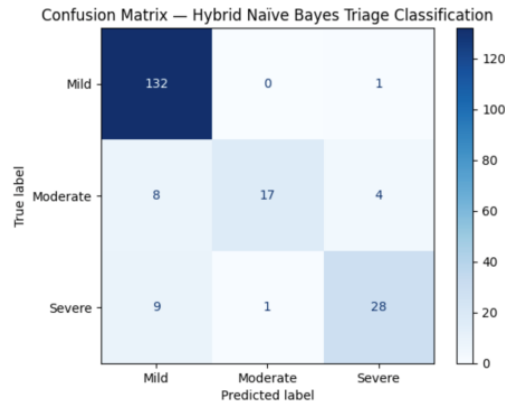


Fig. 2. Confusion Matrix of Hybrid Gaussian Naïve Bayes model

The confusion matrix (Fig.2) illustrates the distribution of true versus predicted classes. The model achieved high accuracy in identifying Mild cases, correctly classifying 132 out of 133 samples, with only one mild case misclassified as severe. Moderate cases were slightly more challenging, with 17 correctly classified, while Severe cases achieved 28 correct predictions out of 38, showing the model's reliable detection of critical patients despite overlapping symptom ranges.

Table 1 Class wise Metrics

Metrics	Mild	Moderate	Severe	Overall
Precision	0.8859	0.9444	0.8485	-
Recall	0.9924	0.5862	0.7368	-
F1-Score	0.9361	0.7234	0.7887	-
Accuracy	-	-	-	0.885

The class-wise precision, recall, and F1-scores are presented in Table 1. Quantitatively, the model achieved a precision of 0.8859, recall of 0.9924, and F1-score of 0.9361 for Mild cases, indicating excellent consistency. For Moderate cases, precision was 0.9444 but recall dropped to 0.5862, revealing that while the model's positive predictions were mostly correct, several moderate cases were underestimated as mild. Severe cases showed balanced performance with precision = 0.8484, recall = 0.7368, and F1-score = 0.7887, demonstrating good sensitivity to critical conditions.

A closer look at the confusion Matrix Fig. 2 we can see that most of the misclassification is between moderate and Severe while there is only one misclassification in Mild class.

The model attained an overall accuracy of 88.5%, a weighted F1-score of 0.877, and a macro F1-score of 0.816. These results validate the effectiveness of the Gaussian Naïve Bayes approach for automated triage, given its computational efficiency and interpretability.

Figure 3 shows how the doctor sees the output of the system and take up the patient and as soon as the doctor dismisses the patient he can press the mark as attended button.

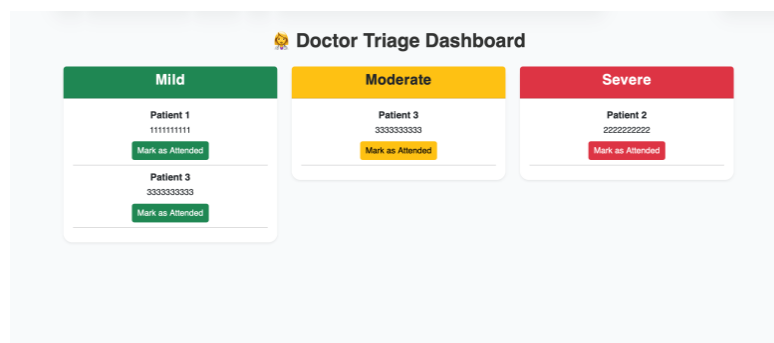


Fig. 3 Doctors Dashboard

5. Conclusion

The objective of this system is to create a straightforward yet efficient telemedicine triage system that could classify patients according to their symptoms and vital signs. Using the Hybrid Gaussian Naïve Bayes model to correctly classify the model as mild, moderate and severe. The technique is helpful because it doesn't require complex computing to make correct triage judgements even with less hardware.

The Doctor and Patient Interfaces are made especially to make the system more user friendly for everyone. In addition to saving time, this arrangement made it obvious which patients need urgent attention. Together, these characteristics transformed a basic categorization model into a functional telemedicine tool that can support in-person consultations.

However, there is still a lot of improvement that can be done. Like instead of simulated dataset a real dataset with proper ground truth can be adopted to make the system more robust and accurate. Training the model on larger, real-world clinical datasets would be the next crucial step to enhancing its accuracy and adaptability to various medical diseases. The system can also be added with some Clinical Decision Support System (CDSS) and e-Prescription can be added to make the system end to end along with video call method.

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Machine Learning Applications in Biomedical Telemetry Systems for Drowsiness Detection: A Review

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Abstract. This article presents an overview of the evolving role of biomedical telemetry systems in developing remote patient monitoring. Traditional telemetry technologies are plagued by limitations such as bulky devices, wired dependency, and lack of flexibility, restricting their clinical usability. Recent breakthroughs have enabled wireless data transmission, wearable sensor embedding, and artificial intelligence integration for improved accuracy and efficiency. Among these, machine learning (ML) methods have shown remarkable promise in classifying physiological signals, detecting abnormalities, and assisting in clinical decision-making. This paper reviews the latest developments in biomedical telemetry, focusing on the use of ML in analyzing biosignals, particularly EEG-based drowsiness detection systems. Despite notable progress, challenges such as signal noise, small datasets, and limited real-time validation remain significant barriers. The paper concludes that the future potential of biomedical telemetry lies in adaptive ML frameworks trained on diverse patient datasets to ensure robust, real-time health monitoring. Such advancements can lead to more accessible, accurate, and patient-centered intelligent healthcare systems.

Keywords. Biomedical telemetry, wearable sensors, machine learning, artificial intelligence, remote monitoring.

1. Introduction

Biomedical telemetry plays an essential role in modern healthcare by enabling real-time remote monitoring of patients' vital signs. It allows clinicians to assess physiological parameters such as heart rate, oxygen saturation, and brain activity from a distance, reducing hospital visits and improving early diagnosis.

Traditional telemetry systems rely heavily on wired configurations, limiting patient movement and comfort. Recent advancements in sensor miniaturization, wireless communication, and low-power electronics have given rise to portable and wearable telemetry devices capable of continuous data acquisition.

Machine learning has revolutionized the analysis of biomedical data by allowing automatic detection and classification of complex physiological patterns. ML models, when integrated into telemetry systems, can identify early warning signs of medical conditions, automate diagnosis, and support clinical decisions. A key example of ML integration in telemetry is electroencephalography (EEG)-based systems used for drowsiness detection, where algorithms classify alertness states using brain signal patterns. These systems demonstrate the potential of combining ML with biomedical telemetry for intelligent and adaptive patient monitoring.

2. Background and Motivation

Remote monitoring and real-time analysis have become priorities in healthcare due to the growing demand for non-invasive and continuous patient tracking. Biomedical telemetry systems provide this capability by transmitting physiological data wirelessly to healthcare centers or cloud-based analytics platforms. The integration of ML enables these systems to perform automated data interpretation, significantly enhancing their diagnostic power.

In clinical environments, telemetry systems monitor cardiac rhythms, respiratory rates, and neural activity. Outside hospitals, similar systems are applied in wearable fitness trackers and assistive devices. Despite their benefits, conventional telemetry setups face issues such as electrode interference, data loss, and difficulty in continuous signal analysis. ML-based algorithms offer solutions by improving signal classification accuracy and noise robustness.

EEG telemetry, in particular, provides detailed insights into neural states and is widely used in applications such as epilepsy diagnosis, sleep monitoring, and drowsiness detection. ML algorithms applied to EEG data can recognize specific brainwave patterns associated with fatigue, alertness, or cognitive workload. This review emphasizes how integrating ML with telemetry systems enhances both clinical and everyday monitoring by making devices intelligent, efficient, and adaptive.

3. Literature Review

The recent trend in biomedical telemetry research shows a major shift toward machine learning and deep learning techniques for analyzing physiological signals. Ten representative studies published between 2021 and 2025 were reviewed to highlight ML's role in EEG-based drowsiness detection - a model example of advanced telemetry integration.

- **Fouad (2023)** developed an EEG-based fatigue detection system using multiple ML classifiers, including SVM, KNN, and MLP, achieving nearly 99% intra-subject accuracy and 96% inter-subject accuracy [1].
- **Zayed et al. (2024)** improved on traditional methods by introducing a feature selection approach for EEG signals, achieving 99.84% accuracy using SVM and MLP [2].
- **Zayed et al. (2025)** further proposed a hybrid CNN-SVM framework that used 2D EEG scalograms for robust inter-subject performance, achieving 98.33% accuracy [3].
- **Obaidan et al. (2024)** introduced EEG_DMNet, a multi-scale 1D CNN model that achieved 97.03% accuracy using the SEED-VIG dataset [4].
- **Gao et al. (2023)** employed a CNN-RNN model based on EEG spectrograms, achieving 88.4% accuracy for fatigue classification [5].
- **Alghanim et al. (2024)** designed a hybrid Inception-Dilated ResNet model, reaching 98.8% accuracy across datasets [6].
- **Guarda et al. (2022)** implemented a Capsule Network architecture for EEG-based drowsiness detection, achieving 86.4% accuracy and improved feature representation [7].
- **Liu et al. (2023)** developed an attention-based Graph Convolutional Network (GCN) that modeled spatial relationships between EEG electrodes, achieving 89.9% accuracy [8].
- **Fang et al. (2023)** proposed AGL-Net, a CNN-LSTM hybrid with lightweight architecture and attention mechanisms, achieving 87.3% accuracy [9].
- **Cui et al. (2022)** introduced a compact single-channel CNN achieving 73.2% cross-subject accuracy while emphasizing model interpretability [10].

These studies collectively demonstrate how machine learning techniques-ranging from traditional classifiers to advanced deep neural networks-enable efficient telemetry signal analysis, improving fatigue detection and potential real-time clinical monitoring (Table 1).

Table 1

Paper (Year)	Core ML/DL Technique	Input Data Type	Key Metrics / Accuracy	Main Strengths / Innovation	Limitations Noted
Kaveh et al. (2024)	SVM	Wireless Ear-EEG	93% Accurac y	Discreet, comfortable in-ear sensing; low motion artifacts	Small dataset; lab- based study
Zhu et al. (2021)	CNN (Inception- CNN)	EEG Spectrogra ms	95.6% Accurac y	Automatic feature extraction from 2D representati ons	Dataset size; potential overfitting
Zayed et al. (2025)	Hybrid CNN–SVM	EEG Scalograms	98.3% Accurac y	Combines strengths of DL feature learning and SVM classificatio n	Computational cost of 2D conversion
Hassan et al. (2025)	Transformer (ViT)	Facial Video Frames	99.15% Accurac y	Contactless, robust to head movements; high accuracy	Privacy concerns; lighting dependency; high compute load

Chen et al. (2023)	Capsule Network	Multi-channel EEG	94.2% Accuracy	Better interpretability; captures spatial-temporal relations	Complex architecture; limited dataset
Zayed et al. (2024)	SVM + Feature Selection	EEG Data	99.8% Accuracy	Feature-optimized model achieving near-perfect detection	Limited subject diversity
Obaidan et al. (2024)	1D CNN (EEG_DMNet)	Raw EEG	97.03% Accuracy	Multi-scale feature extraction; efficient model	Dataset imbalance
Gao et al. (2023)	CNN-RNN	EEG Spectrograms	88.4% Accuracy	Sequential feature learning for fatigue detection	Moderate accuracy; needs optimization
Alghanim et al. (2024)	Hybrid Inception-ResNet	EEG Data	98.8% Accuracy	Highly generalized hybrid model	Model complexity; high training cost
Cui et al. (2022)	Compact CNN	Single-Channel EEG	73.2% Accuracy	Lightweight; interpretable	Cross-subject variability; reduced accuracy

4. Methodology of Review

The methodology involved systematic selection of research papers focusing on EEG-based ML telemetry systems between 2021 and 2025. Searches were conducted using IEEE Xplore, ScienceDirect, and PubMed with keywords such as *EEG telemetry*, *machine learning*, *drowsiness detection*, and *wearable sensors*. Each study was analyzed for model type, dataset used, preprocessing methods, and classification results. This qualitative synthesis identifies performance benchmarks and common algorithmic approaches used for telemetry signal interpretation.

5. Summary of Findings

The reviewed literature reveals several consistent patterns and achievements:

- **High Accuracy and Reliability:** Nearly all models achieved above 85% accuracy, with CNN-based models outperforming traditional ML algorithms.
- **Feature Extraction and Optimization:** Using spectrograms and wavelet scalograms improved performance by preserving both time and frequency features.
- **Reduced Electrode Dependency:** Some models demonstrated high accuracy using minimal electrodes (e.g., ear-EEG or single-channel setups).
- **Cross-Subject Adaptability:** Transfer learning and hybrid architectures improved generalization across individuals.
- **Energy Efficiency:** Lightweight models such as AGL-Net showed that ML algorithms could be optimized for embedded telemetry applications.

These findings confirm the practicality of integrating ML with biomedical telemetry for real-time monitoring and decision support.

6. Discussion of Limitations

While the reported accuracy rates are impressive, several challenges persist in the deployment of ML-based telemetry systems:

- **Limited Dataset Diversity:** Many studies use small, controlled datasets, which restrict model generalizability.
- **Inter-Subject Variability:** EEG signals vary widely across users, requiring calibration or adaptive algorithms.
- **Real-World Validation:** Most models are tested in laboratory environments rather than real-time clinical settings.
- **Hardware Constraints:** High computational requirements make it difficult to deploy complex DL models on portable telemetry devices.
- **Signal Quality Issues:** Movement artifacts and electrode noise can degrade signal clarity and classification accuracy.

Addressing these issues is vital for transitioning telemetry research from laboratory prototypes to clinical and consumer applications.

7. Future Work Directions

Future efforts should focus on the following areas:

- **Multimodal Data Fusion:** Integrating multiple biosignals (EEG, ECG, PPG, motion) can improve diagnostic accuracy.

- **Adaptive Learning Systems:** Developing self-calibrating ML models to handle individual variability.
- **Edge Computing and Energy Optimization:** Creating efficient AI models capable of running on wearable telemetry devices.
- **Data Sharing and Standardization:** Building large, annotated public datasets to support reproducibility and benchmarking.
- **Explainable AI:** Ensuring transparency in model decisions to enhance trust in clinical adoption.

Such advancements will bring telemetry closer to intelligent, patient-specific health monitoring systems.

8. Conclusion

This paper reviewed the current state of biomedical telemetry and highlighted how machine learning techniques are transforming remote patient monitoring. By analyzing ten recent EEG-based drowsiness detection studies, it was found that ML algorithms can classify physiological states with remarkable precision. Despite existing challenges like limited data and variability, progress in sensor miniaturization, algorithm optimization, and hardware integration promises a future where wearable telemetry systems deliver continuous, intelligent healthcare support. Machine learning has thus become a cornerstone of the next generation of biomedical telemetry—paving the way for accurate, accessible, and personalized patient monitoring.

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Exploring the Potential of Bacteria-Mediated Chromium Chelation in Biomedical Waste Contaminated Water

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Abstract. Chromium pollution in biomedical wastewater is a serious public and ecological health risk because of its high toxicity, carcinogenicity, and aquatic bioaccumulation potential. Traditional remediation processes like chemical precipitation, ion exchange, and membrane filtration are energy intensive, expensive, and produce secondary pollutants, thus restricting their use on a large scale and longevity. Bacteria-assisted chromium chelation presents a sustainable, green, and its effective bioremediation option for the toxic chromium species. Bacteria have inherent processes e.g., biosorption, bioaccumulation, enzymatic reduction, and secretion of extracellular polymeric substance (EPS) that allow chelation and immobilization of toxic chromium compounds. The cell wall of the bacteria, which is loaded with carboxyl, hydroxyl, amino, and phosphate moieties, favours binding of chromium ions and overall removal. Studies have established that bacterial species such as *Pseudomonas*, *Bacillus*, and *Escherichia coli* efficiently reduce the Chromium concentrations to environmental safe limits. In addition, incorporating bacterial bioremediation with nanomaterials, biofilm reactors, or genetic engineering greatly enhances the Chromium removal efficiency, stability, and adaptability under different wastewater conditions. This review highlights the mechanisms, benefits, and drawbacks of bacteria-mediated chromium chelation and its potential as a green, economical, and sustainable method for chromium-contaminated biomedical wastewater treatment and global environmental and the human health protection.

Keywords. Bacteria; Chromium; waste water; Chelation; remediation; Biomedical contaminated sites.

1. Introduction

Chromium pollution from industrial and biomedical effluents is a severe environmental and public health issue because of its toxic, mutagenic, and carcinogenic properties, especially in the hexavalent form (Cr^{6+}). Traditional techniques for chromium removal, including chemical precipitation, ion exchange, and membrane filtration, tend to be costly and produce secondary pollutants. Bacteria-mediated chelation of chromium provides a cost-effective and environmentally friendly solution for decontaminating water with chromium [1]. Some bacteria have the inherent capacity to convert poisonous Cr^{6+} to less toxic trivalent form (Cr^{3+}) or chelate chromium ions by extracellular polymeric substances and biosorption processes. Screening of the possibilities of these bacterial systems from biomedical polluted water sources may lead to the detection of effective strains for bioremediation under natural

conditions. This method not only supports sustainable wastewater treatment but also helps in the creation of green technologies for the restoration of the environment.

Biomedical technology, as applied to bacteria-mediated chromium chelation activities from biomedical contaminated water areas, is the utilization of biological and technological concepts to track, control, and abate pollution by biomedical waste. It entails the utilization of microbial systems and biotechnological instruments for detecting, isolating, and promoting bacteria with the ability to detoxify heavy metals such as chromium from biomedical effluents. A schematic of Graphical Abstract (GA) is shown in Fig 1 (prepared in biorender.com). This technology combines microbiology, environmental biotechnology, and biomedical waste management in the generation of environmentally friendly solutions for minimizing toxic metal levels. Through bacterial chelation and biotransformation processes, biomedical technology facilitates the secure treatment and recycling of polluted water, hence safeguarding ecosystems and public health [2]. Biomedical technology in the context of chromium chelation by bacteria involves the utilization of technological and biological principles to track, control, and clean up chromium contamination resulting from biomedical and healthcare waste streams. Biomedical wastewater generally comprises leftover chemicals, disinfectants, and heavy metals such as chromium that arise from laboratory operations, diagnostic reagents, medical device production, and hospital effluents [3]. Biomedical technology seeks to couple microbiological systems with contemporary engineering methods for the purpose of designing sustainable treatment strategies. On this occasion, naturally metal-binding and detoxifying bacteria are used as bio-agents to sequester and convert toxic chromium forms to less toxic analogues through an environmentally friendly alternative to traditional chemical treatment processes that tend to be costly and generate secondary pollutants [4]. In addition, bio-mediated technology of bacteria-assisted chromium chelation involves the search and design development and optimization of biotechnological means like biofilm reactors, microbial consortia, and genetically engineered strains for achieving better chromium removal efficacy and flexibility in actual wastewater conditions. Utilizing microbial metabolism, enzyme systems, and extracellular polymeric substances, this technique enables simultaneous detoxification and recovery of precious metals from waste, thereby being consistent with circular bioeconomy principles. Accordingly, biomedical technology acts as an intermediary between microbiology, biotechnology, and environmental engineering—to facilitate the development of new, environmentally friendly, and economical solutions for chromium pollution alleviation from biomedical wastewater sources while protecting human and environmental health.[5].

2. Current Scope in bacteria-mediated Chromium chelation activities from biomedical contaminated water sites

The present scale of bacteria-mediated chromium chelation in biomedical-contaminated water ranges from laboratory mechanistic investigations to pilot-scale applications, with increasing focus on scaling up promising strains and consortia to integrated treatment units. In the laboratory bench, scientists are charting mechanisms (biosorption, enzymatic $\text{Cr(VI)} \rightarrow \text{Cr(III)}$ reduction, efflux, bioaccumulation and EPS-mediated sequestration) and designing strong species (e.g., *Bacillus*, *Pseudomonas* and mixed native consortia) which are resilient to common biomedical effluent stresses including high organic load, antibiotics and combined pollutants [6]. Applied work increasingly investigates biofilms, immobilized cells and mixed microbial consortia in order to enhance stability and reusability, and a number of investigations describe pilot-scale bioreactors or hybrid systems (biological + adsorption/chemical polishing) demonstrating good chromium removal under practical

conditions. Technological advances in omics, adaptive laboratory evolution and synthetic biology are applied to increase rates of reduction, tolerance to stress and range of substrates, but electron donors, redox mediators and co-treatments are also investigated in studies to increase in situ reduction activity. Even with these improvements, however, the technology still lags behind in scale-up issues (variable effluent composition, long-term performance, regulatory acceptance, and metal-laden biomass safe disposal), so the short-term scope is realistic: integrate bacterial chelation with standard polishing steps, focus pilot trials on actual biomedical wastewater, and apply genomics-led strain/consortium selection to close laboratory success and field deployment. The present range of bacteria-mediated chromium chelation at biomedical contaminated water locations is quickly widening as scientists investigate its viability as a cheap, non-polluting, and effective bioremediation method. Several bacterial species including *Pseudomonas*, *Bacillus*, *Escherichia coli*, and *Enterobacter* have been shown to be highly efficient in the removal of chromium by processes such as biosorption, bioaccumulation, and enzymatic reduction. These bacteria can transform lethal hexavalent chromium (Cr^{6+}) to its less harmful trivalent form (Cr^{3+}), thus minimizing environmental and health hazards posed by heavy metal contamination. Microbiological and biotechnological advancements have enabled the isolation, identification, and improvement of efficient chromium-resistant bacterial strains from contaminated environments, enhancing their adaptability and efficiency under different pH, temperature, and salinity conditions characteristic of biomedical wastewater [7]. Furthermore, combining bacterial chelation with newer technologies like nanomaterials, biofilm reactors, and genetic modification has broadened the horizon of this technique even more. Bacterial systems assisted with nanoparticles increase metal-binding capacity and electron transfer, whereas biofilm-based systems enhance microbial stability and continuous treatment efficacy [8]. Genetic alterations and synthetic biology resources are utilized to design bacterial strains with enhanced chromium reduction pathways, increased enzyme catalytic ability, and elevated metal tolerance. The emphasis now is also placed on the construction of scaled-up bioreactors and hybrid systems that integrate bacterial cleanup with physical or chemical treatments for efficient large-scale treatment of biomedical wastewater. In total, the widening reach of chromium chelation mediated by bacteria mirrors its increasing significance as a foundation of contemporary eco-biotechnological strategies in the quest for clean water, pollution abatement, and biomedically sound waste treatment [9].

3. Model of bacteria-mediated Chromium chelation activities from biomedical contaminated water sites

The bacteria-mediated chelation model of chromium from biomedical polluted water sources describes the sequential physicochemical and biological mechanisms of chromium detoxification by microbial systems. In this model, chromium-polluted effluents initially pass through bacterial interaction, wherein particular species of bacteria adsorb and chelate chromium ions via their cell surface functional groups like carboxyl, hydroxyl, and amino groups. This is succeeded by enzymatic reduction, wherein harmful hexavalent chromium ($\text{Cr}(\text{VI})$) is reduced to the lower-toxicity trivalent form ($\text{Cr}(\text{III})$), usually stabilized by chelation or formation of a complex with bacterial metabolites or extracellular polymeric substances. The process as a whole is controlled by environmental conditions such as pH, temperature, redox potential, and availability of organic matter. The model combines adsorption, biotransformation, and precipitation processes to outline the dynamic chromium removal from polluted water, hence predicting bacterial detoxification effectiveness under disparate environmental and operational conditions [10]. Bacteria-mediated chromium chelation model

from biomedical contaminated water sources is premised on the inherent metabolic and structural potential of bacteria to immobilize and detoxify substances like toxic chromium species, specifically hexavalent chromium (Cr^{6+}). Upon introduction of bacteria into chromium-polluted wastewater, their cell walls that contain abundant functional groups like carboxyl, hydroxyl, amino, and phosphate moieties enable the first adsorption and coordination of chromium ions through surface complexation and electrostatic forces. This biosorption process aids in quick dissolved chromium removal from the liquid phase. Subsequent to adsorption, some bacterial strains employ enzymatic reduction processes in which Cr^{6+} is reduced to less toxic trivalent Cr^{3+} by intracellular or membrane-bound reductase enzymes [11]. The lower chromium precipitates in the form of insoluble compounds or gets sequestered in the extracellular polymeric substances (EPS) released from bacteria, thus reducing its bioavailability and mobility in water systems. Along with these inherent processes, the model also includes synergistic interactions between environmental parameters and microbial populations that augment chromium elimination efficiency. Biofilm growth on solid supports enables bacteria to operate cooperatively in an EPS matrix produced by themselves, enhancing surface area for binding chromium and providing protection from hostile wastewater environments. The model may also be extended by incorporating other new technologies like nanomaterial supports or genetically engineered bacterial strains to further enhance chromium chelation capacity, enzymatic activity, and system stability. Generally speaking, this model displays a holistic and green bioremediation strategy that not only minimizes chromium toxicity in biomedical wastewater but also enhances sustainable heavy metal pollutant management through the synergistic effect of microbial metabolism, surface chemistry, and contemporary biotechnological advances.

4. Concept of Bacteria-Mediated Chromium Chelation

The mechanism of bacteria-mediated chromium chelation is the capacity of some microorganisms to detoxify, convert, and immobilize carcinogenic chromium species by undergoing biological and biochemical reactions. Chromium in the hexavalent state (Cr^{6+}) is extremely toxic, mutagenic, and carcinogenic and poses critical threats to aquatic ecological systems and human health when discharged through biomedical wastewater. Bacteria have natural defense and adaptation processes that allow them to survive and thrive in metal-polluted environments. Bacteria can adsorb and reduce chromium ions through mechanisms like biosorption, bioaccumulation, bioreduction, and extracellular polymeric substance (EPS) production [12]. In biosorption, chromium ions bind with the bacterial cell wall, which is composed of functional groups such as carboxyl, hydroxyl, phosphate, and amino moieties. At the same time, enzymatic reduction permits bacteria to reduce Cr^{6+} to the less toxic trivalent chromium (Cr^{3+}), precipitating or forming stable complexes and reducing its solubility and mobility in water systems. This bio-chelation process is both environmentally friendly and economical compared to other traditional physicochemical treatments. The effectiveness of bacterial chromium chelation relies on various parameters such as bacterial strain type, environmental conditions (ion concentration, temperature, and pH), and the availability of other organic or inorganic substances [13]. Some bacterial genera like *Pseudomonas*, *Bacillus*, *Escherichia coli*, and *Enterobacter* have been well researched for chromium-binding and reduction properties. In addition, biofilm development can reinforce the chelation process where bacterial populations synthesize an extracellular protective EPS matrix enhancing stability and stress resistance. In conclusion, the notion of bacteria-mediated chelation of chromium is a new biotechnological strategy for biomedical wastewater treatment that further supports pollution sustenance and the safeguarding of ecological and human health.

5. Biosorption and Bioaccumulation

Biosorption and bioaccumulation are the two major mechanisms through which bacteria remove and immobilize chromium from the contaminated environment. Biosorption is a non-active process involving the adsorption of chromium ions onto the bacterial cell surface, where the chromium ions attach to negatively charged functional groups on the cell wall [13]. This process does not involve metabolic energy and is primarily caused by electrostatic attraction, ion exchange, complexation, and surface precipitation. A typical schematic of the process of bioaccumulation and biosorption is shown in Fig. 1 (prepared in biorender.com). Bioaccumulation, in contrast, is an energetic process that involves the passage of chromium ions into the bacterial cell via membrane transport systems with subsequent intracellular sequestration or transformation. Bacteria for bioaccumulation are able to accumulate chromium within intracellular storage compartments, which decreases its bioavailability and toxicity in the external environment. These processes altogether contribute significantly to decreasing chromium concentration in biomedical wastewater.

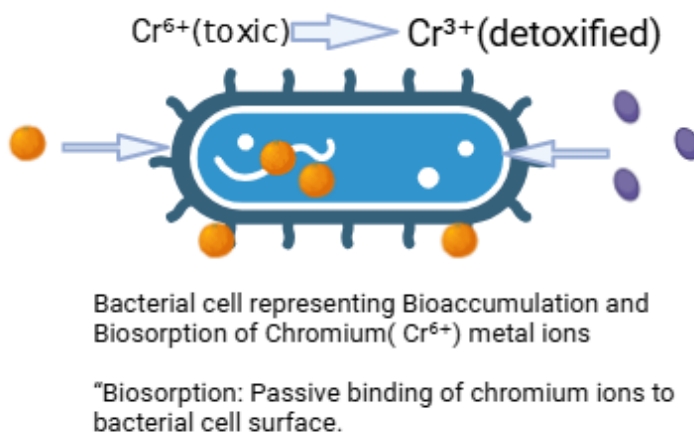


Fig. 1. Chromium Chelation by bacteria — Biosorption and Bioaccumulation mechanism

6. Enzymatic Reduction of Cr⁶⁺ to Cr³⁺

Enzymatic reduction of hexavalent chromium (Cr⁶⁺) to trivalent chromium (Cr³⁺) is an important detoxification process in bacterial chromium chelation [14]. This decrease is facilitated by chromate reductases in bacteria's cytoplasm and periplasmic regions. Cr⁶⁺ is an electron acceptor used in bacterial metabolism, with reducing substances like NADH or NADPH donating electrons to reduce Cr⁶⁺ to the less toxic, less soluble form of Cr³⁺. A schematic of the process is depicted in Fig. 2 (prepared in biorender.com). The formed Cr³⁺ is prone to precipitate or stabilize complexes with organic and inorganic molecules, facilitating immobilization. Through this enzymatic action, chromium is not only detoxified but also

enables bacteria to resist metal stress, ensuring their survival in contaminated biomedical wastewater.

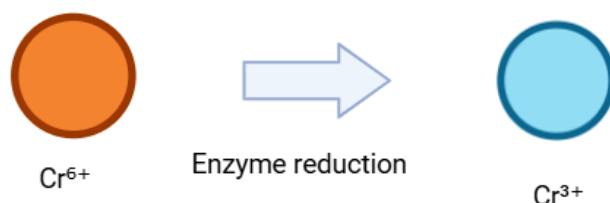


Fig 2. Enzymatic reduction process of Cr^{6+} to Cr^{3+}

7. Role of Extracellular Polymeric Substances (EPS)

Bacteria-secreted Extracellular Polymeric Substances (EPS) are crucial in chelating chromium by functioning as a natural bio-sorbent and defensive barrier. EPS are made up of polysaccharides, proteins, lipids, and nucleic acids with more than one functional group available for binding metal ions [12]. A typical schematic of the role of EPS is shown in Fig.3 (prepared in biorender.com). The EPS matrix creates a hydrated, sticky surface that promotes the adhesion of bacteria to surfaces and allows for the entrapment of chromium ions. EPS also shields bacterial cells from oxidative stress due to Cr^{6+} toxicity, aids in biofilm formation, and enhances the general metal tolerance of bacterial populations. The presence of EPS greatly enhances available surface area for chromium adsorption and hence the removal efficiency in wastewater systems.

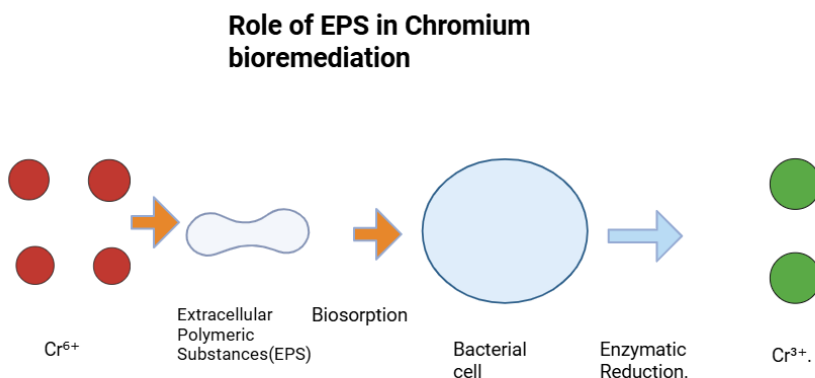


Fig. 3. Implication of EPS in chromium ion chelation cum reduction in bacterial mediated process

8. Functional Groups Responsible for Binding of Metals

The EPS matrix and bacterial cell wall both have various functional groups responsible for the chelation and binding of chromium ions. These functional groups include carboxyl (-COOH), hydroxyl (-OH), amino (-NH₂), phosphate (-PO₄³⁻), and sulfhydryl (-SH) groups [12]. A typical schematic demonstrating the mechanism of chromium ions absorption to functional groups at EPS surface in bacteria mediated chromium chelation is shown in Fig. 4 (prepare in biorender.com). These functional moieties present active sites for the interaction of chromium ions through coordination, ion exchange, and covalent binding. For example, carboxyl and phosphate groups tend to coordinate positively charged chromium species by electrostatic forces, while amino and hydroxyl groups coordinate through coordination complexes. The number and distribution of these functional groups on bacterial surfaces dictate the metal-binding capacity and the overall efficiency of chromium removal. Collectively, these functional groups make bacterial systems highly effective bio-chelators for treating chromium-contaminated biomedical wastewater.

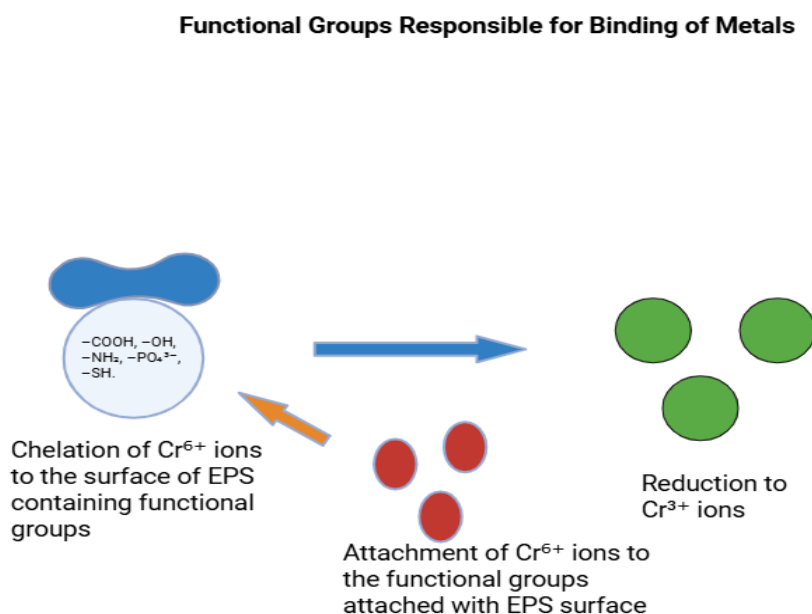


Fig. 4. Role of Functional groups in Chromium chelation mechanism using bacteria

9. Bacterial Strains with Chelation Potential

Some bacterial strains have very high chromium chelation capacity because they can tolerate, bind, and reduce toxic chromium species to less toxic ones. Some of the most researched include *Pseudomonas*, *Bacillus*, *Escherichia coli*, *Enterobacter*, and *Acinetobacter species*. They are highly adaptable to polluted environments and have varying metabolic capabilities that allow for chromium removal via biosorption, bioaccumulation, and enzymatic reduction [4, 7]. For instance, *Pseudomonas aeruginosa* and *Bacillus subtilis* have been reported to convert hexavalent chromium (Cr⁶⁺) into trivalent chromium (Cr³⁺) with high

efficiency due to the availability of chromate reductase enzymes and cell wall structures that are strong and rich in active binding sites. Equally, *Escherichia coli* utilizes intracellular redox processes for detoxification of Cr^{6+} , whereas *Enterobacter cloacae* is characterized by high tolerance and chromium-binding capacity via its extracellular polymeric substances (EPS) that facilitate improved metal ion sequestration and cell protection against toxicity. Existing research has also centered on the possibility of mixed microbial consortia and genetically modified bacterial strains for efficient chromium chelation of biomedical wastewater. The cooperation among various species of bacteria in consortia enables enhanced chromium removal due to mutualistic metabolic pathways and enhanced biofilm strength. Genetic engineering of bacteria like *Pseudomonas putida* and *Bacillus megaterium* has been investigated to overexpress reductase enzymes of chromium or enhance the production of EPS so that metal-binding efficiency and stress resilience can be enhanced. In addition, advancements in nanobiotechnology and immobilized bacterial systems have further improved the practical usability and resilience of these strains to changing wastewater conditions [7]. In general, these bacterial strains are a promising, environmentally friendly solution for effective chromium-contaminated biomedical wastewater treatment in favour of sustainable and biologically mediated remediation practices.

10. Biomedical Technology Applications

Biomedical technology uses of bacteria-mediated chromium chelation are centered around combining microbial systems with engineered and biotechnological devices to enhance the reliability and efficiency of chromium removal from biomedical wastewater [15]. The majority of applications for immobilized bacterial systems and biofilm reactors are based on supporting microbial community growth in a controlled environment, enabling bacteria to settle on surfaces, develop protective biofilms, and achieve high cell density for repeated wastewater treatment. These systems improve chromium adsorption and biotransformation by presenting a stable microenvironment that shields bacteria from the stress of toxic metals and allows for extended activity. Furthermore, utilization of sophisticated bioreactors allows for optimization of conditions like pH, temperature, and availability of nutrients, further enhancing the removal efficiency of toxic chromium species [5]. Other emerging biomedical technology strategies involve the application of nanomaterials and genetic manipulation to enhance bacterial chelation capacity. Nanoparticles, when mixed with bacterial cells, enhance electron transfer, redox reactions, and adsorption capacity for chromium ions. Genetic and metabolic engineering strategies enable the creation of bacterial strains with increased chromate reductase activity, heavy metal tolerance, and the production of extracellular polymeric substances (EPS), which enable metal binding and immobilization. These integrated techno-strategies render bacterial chromium chelation more scalable, stable, and responsive to varying wastewater conditions, offering an environmentally friendly, cost-effective, and sustainable approach for biomedical wastewater treatment and prevention of environmental and human health hazards of heavy metal pollution.

11. Current Scope and Research Advances

The existing range of chromium chelation mediated by bacteria has extensively expanded with scientists persistently investigating microbial capability in sustainable biomedical wastewater treatment. Experiments in recent past have shown that several bacterial genera, such as *Pseudomonas*, *Bacillus*, *Escherichia coli*, *Enterobacter*, and *Acinetobacter*, exhibit satisfactory chromium tolerance and removal capacities via biosorption, bioaccumulation, and enzymatic reduction. These microorganisms can thrive under stressful

wastewater environments and efficiently convert toxic hexavalent chromium (Cr^{6+}) to its less toxic trivalent species (Cr^{3+}) to reduce its environmental impact. The growing knowledge of bacterial metabolism, enzyme kinetics, and cell wall chemistry has also enabled enhanced selection and optimization of microbial cultures for particular wastewater environments. In addition, mixed bacterial consortia have come into the limelight, as mixed microbial synergies tend to increase chromium detoxification performance and stability over single-strain systems. Recent developments also focus on integration of bacterial remediation with innovative technologies to address limitations including poor performance under conditions of extreme pH or temperature and sluggish reduction rates. The integration of nanomaterials into bacterial systems has been effective in promoting chromium adsorption and redox reactions through optimized surface interaction and electron transfer. Likewise, biofilm reactors and immobilized bacterial systems provide higher resistance against toxic metal concentrations and allow continuous operation treatment. Genetic engineering and synthetic biology are further transforming this discipline by creating altered bacterial strains with overexpressed chromate reductase enzymes, increased EPS production, and enhanced resistance to toxic conditions. Generally, these developments suggest an increasing capability for bacteria-assisted chromium chelation to emerge as a mass-level, eco-friendly means of biomedical wastewater treatment towards global sustainability and environmental conservation efforts.

12. Challenges and Limitations

Notwithstanding its huge potential, bacteria-mediated chromium chelation suffers from a number of challenges and limitations that are restraining its large-scale application to biomedical wastewater treatment. One of the biggest challenges is the sensitivity of the bacterial system to environmental factors like pH, temperature, and the availability of competing ions or toxic compounds in wastewater. Changes in these variables have a significant impact on the growth of bacteria, enzyme activity, and efficiency of chromium reduction. In addition, it is challenging to retain the viability and metabolic activity of bacteria in the presence of high levels of chromium or co-contaminating heavy metal pollutants because high toxicity will harm cellular components and suppress chelating activities. The slow kinetics of biological reduction is another limitation compared to chemical treatments, which can slow down the overall treatment rate in high-capacity wastewater systems. In addition, upscaling from laboratory to large-scale industrial application continues to be problematic owing to operational issues and the demands of maintaining controlled conditions in order to support bacterial performance. A further major limitation is concerned with long-term stability and preservation of bacterial cultures within bioreactors or natural wastewater treatment systems. Ongoing exposure to changing waste compositions and stress conditions may result in reduced microbial activity or metal-removal efficiency loss over time. The challenges associated with the safe disposal and handling of the treated metal-loaded biomass are also present, as unsafe disposal may result in secondary pollution. Maintaining bacterial consortia, optimizing nutrient supply, and ensuring performance robustness under diverse wastewater conditions are also issues of economic viability. In order to overcome these challenges, recent studies are aiming to increase bacterial stability and tolerance using genetic modification, immobilization procedures, and incorporation of hybrid systems that utilize biological and physicochemical processes. Overcoming these constraints will be instrumental in developing bacteria-based chromium chelation as a dependable, scalable, and environmentally friendly technology for biomedical wastewater treatment.

13. Future Prospects and Research Directions

The prospects for future applications of bacteria-mediated chelation of chromium are very promising, with current research further developing its efficiency, flexibility, and scalability in practical wastewater treatment. A major direction of current research is the genetic and metabolic modification of bacterial strains to enhance their tolerance of chromium, enzymatic reducing ability, and the production of extracellular polymeric substance (EPS). By controlling certain genes involved in the uptake and reduction of chromium, researchers can engineer bacteria with improved detoxification and survival at harsh wastewater conditions. Moreover, breakthroughs in synthetic biology and omics sciences (genomics, proteomics, and metabolomics) are assisting in deciphering microbial pathways and refining bacterial metabolism for better chelation. Another new frontier is microbial consortia and biofilm-based systems, which facilitate cooperative interactions among various bacterial species to achieve greater stability, robustness, and metal-removal efficacy.

Future work also seeks to combine bacterial chelation with nanotechnology, membrane systems, and bio-electrochemical reactors to develop hybrid bioremediation platforms with improved chromium removal performance. Metal adsorption, enzyme activity, and redox reactions can be enhanced by nanoparticle-assisted bacterial systems, whereas bio-electrochemical systems enable the generation of energy from treatment, thereby increasing the sustainability. Pilot-scale bioreactor designs and in-situ bioremediation approaches in biomedical wastewater treatment plants will be studied further to take laboratory successes to practical levels. Additionally, establishing eco-safe strategies for metal recovery and biomass reuse might provide economic benefits and favour circular bioeconomy models. In summary, the prospects for bacteria-mediated chromium chelation are multidisciplinary innovation—the synergy of microbiology, biotechnology, and environmental engineering—to realize effective, clean, and affordable methods for preventing heavy metal contamination and ensuring environmental and human well-being.

14. Conclusion

Bacteria-assisted chromium chelation is an effective, green, and sustainable method for the elimination of toxic chromium species from biomedical contaminated wastewater. Different bacterial strains like *Pseudomonas*, *Bacillus*, *Escherichia coli*, and *Enterobacter* showed high chromium-removing capability through mechanisms such as biosorption, bioaccumulation, enzymatic reduction, and the secretion of extracellular polymeric substances (EPS). These biological processes efficiently reduce hexavalent chromium (Cr^{6+}) to its less toxic trivalent state (Cr^{3+}), thus lowering its solubility and bioavailability. Incorporation of sophisticated technologies like nanomaterials, biofilm reactors, and genetic engineering has also improved bacterial chelation efficiency, responsiveness, and system stability under fluctuating wastewater conditions. Though there are challenges in scaling up the process and preserving bacterial activity in extreme conditions, recent studies present exciting developments that make bacterial chelation a potential alternative to traditional physicochemical processes. The effective use of bacteria-mediated chromium chelation carries important implications for environmental and human health. By minimizing chromium toxic concentrations in biomedical wastewater, the process inhibits aquatic ecosystem contamination, safeguards biodiversity, and reduces heavy metal entry into the food chain. Detoxification of Cr^{6+} also reduces the threats of carcinogenic, mutagenic, and organ-disrupting effects on humans using contaminated water sources. In addition, as an eco-friendly and low-cost technology, bacterial chelation follows the international sustainability goals and environmental protection regulations to minimize industrial contamination. Overall, using

bacteria-mediated chromium chelation within wastewater treatment processes is conducive to cleaner water resources, ecological balance, and protecting public health and the environment in the long term.

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The Digital Transformation of Talent Acquisition: A Review of AI-Driven Strategies and Ethical Considerations

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Abstract. The paper reviews current trends in talent acquisition, focusing on the digital transformation from traditional to modern recruitment and selection processes. It traces the emergence and development of technology-driven strategies, including e-recruitment, social media sourcing, gamification, and the widespread integration of Artificial Intelligence (AI). The pursuit of operational efficiency through automation is examined in conjunction with the critical need for fairness, bias mitigation, and an enhanced candidate experience. Basic recruitment trends are tracked, including the use of AI for automated resume screening, predictive analytics for candidate matching, and chatbots for applicant engagement. The strategic value of structured interviews, employer branding, and inclusive hiring practices are also considered. A conceptual framework for evaluating the integration of these technologies is implicitly proposed, centered on balancing technological capability with ethical governance. For this purpose, the tension between data-driven objectivity and the risk of algorithmic bias is analyzed. Promising directions for future research are outlined, emphasizing the need for robust auditing of AI systems, exploring hybrid models that retain the human element, and examining the long-term impact of digital tools on workplace diversity and organizational culture.

Keywords. Digital recruitment, artificial intelligence, talent acquisition, algorithmic bias, ethical HRM.

1. Introduction

Attracting, assessing, and acquiring talent is an organizational success pillar and a major factor of competitive advantage in the contemporary, dynamic digital economy. Within the past twenty years, talent acquisition has been shifting towards a paradigm change, leaving behind the old, mostly manual and reactive approaches to talent acquisition and transitioning towards a digitally focused approach. This transformation is defined by the adoption of advanced digital solutions and, most importantly, the use of Artificial Intelligence (AI) to automate and streamline all the phases of the recruitment process and transform Human Resource Management (HRM) not merely into an administrative task but a business value generator.

This paper aims at revising the most important trends in this digital transformation. We combine the results of the latest literature to examine the contemporary methods of recruitment and selection, with particular attention to the strengths, advantages, and limitations of the AI-based strategies. It is the long-term aim to present a concise picture of the state of the current environment, discussing the formation of talent acquisition by technologies such as predictive analytics, chatbots, and automated screening and raising the issue of critical ethical issues, including algorithmic bias and data privacy, to the surface. In this review, the transition of traditional techniques to strategic processes, technology-enabled processes, the effects of the main digital tools on the efficiency and applicant experience, and the necessity of balancing

the idea of technological progress with fairness will be traced and the need to achieve an equal and effective recruitment ecosystem will be discussed.

2. The Evolution from Traditional to Strategic Recruitment

Recruitment in the past has been mostly considered a reactionary and operational process with the sole objective of filling vacancies that are arising at that moment. The manual sifting of resumes, a high dependency on unstructured interviews that are very vulnerable to the human cognitive biases, and a short-term perspective of staffing demand were the main characteristics of this traditional paradigm. The job advertisements were generic, and the process of screening was not very consistent, and the decision made was largely based on the intuition instead of the numbers.

Nevertheless, in the current hyper competitive global talent market, organizations are gradually acknowledging recruitment as not only a support service but as an important strategic business necessity which needs to be closely linked to long-term business goals. Strategic recruitment is, thus, characterized by proactive, data-driven and future-oriented nature and is concerned about the development and sustenance of a sustainable talent pipeline to address both the current and future needs of the organization. The planned development of an employer brand and the methodical exploitation of employee referrals are two main pillars that are an indication of this strategic change.

Employer Branding This entails proactively creating and selling a powerful, positive image of an employer of choice to attract, engage and keep the best talent. An attractive employer brand is an effective way of conveying the culture, values and employee value proposition of the organization to the potential and existing employees. The studies have shown that a good employer brand could positively affect employee satisfaction, engagement, turnover intention, and organizational citizenship behavior. It is an important distinguishing factor which helps to attract candidates who not only fit the skill requirements, but also their mission and ethos.

One of the most effective methods of recruitment has always been Employee Referrals, which involves taking advantage of social networks of existing employees to help bring potential employees. Referred employees tend to perform better at work, have an increased tenure period, record improved job attitude and tend to assimilate more easily into the organizational culture than the non-referred employees. The success of this can be attributed to several reasons: existing employees are able to give realistic job previews, are able to pre-screen prospective employees about their abilities and appropriateness in the culture and provide a signal of trust to the candidate and the company. In most organizations, employee referrals have a substantial proportion of employees who are hired thus their practicality. This shift in strategic thinking focuses on long-term planning, brand development, network leveraging, and data extraction offers the fundamental basis of the need to adopt and efficiently use the updated digital instruments that currently define the modern talent acquisition process. Such mechanisms can help companies to implement strategic projects such as employer branding and referral programs massively and more efficiently than ever before.

3. Key Digital Tools in Modern Talent Acquisition

A wide range of technological advances has helped to speed up and fundamentally change the shift to strategic, digitally enabled recruitment accelerated by substituting traditional processes, often paper-based ones. The COVID-19 pandemic was one of the events that accelerated the use of virtual interviews and remote assessments to an extent that

guaranteed the use of technology in modern hiring and resulted in the popularity of hybrid recruitment models.

3.1. E-Recruitment, Social Media, and Gamification

The first digital transformation saw the shift of recruitment to the online environment. Online job recruitment and company career sites had been the norm in advertising job openings and in receiving applications in electronic form. At the same time, the use of professional social media networks specifically LinkedIn transformed the process of sourcing candidates and now allows recruiters to access large pools of active and passive talent, allowing them to reach out to these individuals and network with them.

Later in the day, gamification has also come in as a new method that aims at increasing engagement and evaluation of the candidates. The game mechanics, challenges, and simulations could be added to the application or testing process so that the companies could make the experience more active, interactive, and enjoyable to the candidates. Through gamified tests, it is possible to get some insight into the problem-solving skills and creativity of candidates, time management, and behavioral characteristics through observing their performances in simulated on-the-job situations. This strategy can possibly provide a more objective estimate than traditional ones and enhance the brand image of the employer, especially to the younger demographics.

3.2. The Role of Artificial Intelligence (AI)

AI is the next frontier of the digitalization of talent acquisition that provides advanced features that automate, optimize, and offer intelligence to the whole recruitment funnel. Sourcing and Screening Resumes Resume screening AI algorithms are very useful in automating the time-consuming procedure of screening resumes. AI tools can read through thousands of applications, identify the relevant skills and experiences and then align them with the job requirement with contextual awareness than simple keyword searches using a combination of Natural Language Processing (NLP) and machine learning and rank the most qualified applicants. This brings high performance, saves vast amounts of time to hire measures, and liberates human recruiters to engage in more strategic and value-creating activities such as candidate relationship building. Candidate Engagement A chatbot is an AI-driven solution that is becoming more popular with companies to improve the candidate's experience by creating instant, 24/7 support. Such virtual assistants can respond to common questions of the candidate, give application status updates, prescreen basic qualification, and even help in setting up the interview. This guarantees a timely, consistent, and sometimes personalized communication that is significant in sustaining the interest of the candidates and creating an image of a modern employer. Assessment and Interviews such as While research shows that recruiters in general are not keen on eliminating human interaction in the interview process, AI is being used in assessment. Online tests and assessments are administered by use of technology and more AI tools, although the validity and ethics of such analysis are contested, are being developed to analyze video interviews in terms of communication patterns, sentiment, and non-verbal cues. Interestingly, it can be proposed that some candidates can feel less performance anxiety and be more at ease during the first stages of the selection process with AI-assisted or chatbot-facilitated interviews than in face- to-face environments. Predictive Analytics predictions such as by using large volumes of historical hiring data (e.g., candidate profiles, assessment results) and post-hiring performance data (e.g. performance reviews, tenure, promotions) to infer patterns and correlations thereby helping predict whether a particular candidate will be successful or retained in a job or within the organizational culture. This allows a more data-driven, strategic hiring process which enhances the quality of hire overall and minimizes expensive turnover.

4. Ethical Considerations and Bias Mitigation

Though the introduction of the digital tools, especially AI, has a massive potential to improve the efficiency, coverage, and anticipatory abilities of the talent acquisition process, it also comes with a lot of ethical issues that should be addressed with critical scrutiny and actively handled. The main challenge is to strike the right balance between the advantages of automation and data analysis and the principle of fairness, transparency, and dignity towards individuals.

4.1. The Duality of Bias

One of the challenges is the recruitment bias. Conventional recruiting techniques particularly unstructured interviews and subjective resume scanning are infamously open to a slew of human mental biases. These are affinity bias (giving preference to people who are close to us), the halo/horn effects (allowing a single positive/negative attribute to dominate the overall judgment) and confirmatory bias (focusing on information that supports our beliefs), and unconscious stereotypical inclinations based around safeguarding attributes such as gender, race, age, and disability.

On paper, AI provides a possible remedy to such human biases. Algorithms can be designed to disregard demographic data and concentrate on objective, job related factors, skills, experience and assessment scores, thereby encouraging merit-based assessment.

The danger is algorithmic bias. The AI systems are trained on the data they learn. In case such historical data signalizes previous discriminatory hiring practices or social injustices (e.g., lack of representation of some population in particular positions), the AI can become trained, institutionalized and even enhanced by said biases on a larger scale. A widely publicized example of an experimental recruiting tool used by Amazon, which was forced to be abandoned after it became trained to rank off resumes with the word women's and prefer men because it had been trained on the historically male-dominated data of applicants, is a bright example of a warning sign.

4.2. Strategies for Promoting Fairness

The complicated method of the issue is necessary to create the real fair and balanced hiring process and address the potential bias of the human decision and technological processes. The Structured Interviews, Inclusive Hiring Practices and Ethical AI Governance are the main strategies that have been identified in the literature. Structured Interviews It involves using standardized and job-related questions that are always directed to applicants, and a preset, behaviorally anchored scoring rubric, is one of the strongest and most empirically validated entry modes of enhancing objectivity, reliability, and predictive validity of interviews and minimizing the impact of interviewer bias. A Beyond designed interview, a group of practices should be implemented by organizations with the goal of expanding the diversity and limiting prejudice at all stages of the funnel. These are listed as blind resume screening (anonymizing applications by removing names, gender indicators and other demographic information and then reviewing them) and forming diverse hiring panels so that a variety of views can be factored into the assessment of the candidate, and targeted outreach to actively recruit members of underrepresented groups and atypical talent pools. It is also important to create non-discriminatory job descriptions in a neutral manner.

Ethical AI Governance such as Fair: In AI-based recruitment, requires a robust governance system that is founded on transparency, accountability, and oversight. This involves the periodic auditing of algorithms to actively identify and prevent possible discriminations in favor of the guarded categories. Giving the candidates an understanding of how AI is utilized during the assessment. Making sure that no critical hiring decisions are

achieved using algorithms only, a critical human-in-the-loop should be provided to review, contextualize, and make final decisions.

4.3. Data Privacy

The large amount of data gathered and processed about the applicants of digital recruitment platforms poses a major ethical and legal burden of concerns on the issue of data privacy. Companies should guarantee high adherence to the changing data protection laws, including European Union General Data Protection Regulation (GDPR). These rules will require the open data collection process, the safe storage, restrictions on the use of data, and give the applicants certain rights to their personal data, such as access, correction, and erasure. Fostering trust in the candidates depends on the ability to show them that there is a desire to be responsible and ethical in handling their sensitive data.

5. A Framework for Modern Recruitment

The evidence that is designed and assembled based on the analyzed literature tends to indicate that the most efficient and ethical paradigm of talent acquisition in the contemporary context is not an all-inclusive takeover by technology, but a mutually reinforcing hybridization model. The strategy is a focus on the effective use of technology to achieve more efficiency, objective, and reach, with a conscious attempt to retain and treasure human judgment in activities that need subtlety, empathy, and sophisticated relationship evaluation.

At the higher end of the recruitment funnel with massive data, repetitive tasks, and high volume, AI and automation prove to be the most valuable. This incorporates Sourcing applicants through large online databanks and business contacts. First-level resume screening and application screening based on objective, pre-set conditions. Responding to regular questions by the candidates and arranging appointments through chatbots.

Technology saves time which would otherwise be used by human recruiters by automating all these stages. This enables them to divert their attention to later phases of the funnel, which involves human capabilities in different aspects (high touch). These involve developing meaningful relations with prospective employees. Interviewing candidates based on their complex behavioral competencies and motivations through in-depth and structured behavioral interviews.

Assessment of the more important but less tangible factors of cultural fitness and compatibility with team dynamics. Coming to the final and multifaceted and context-sensitive decision on hiring, combining information understanding and professional opinion. It is not only necessary to create well-rounded hiring decisions using this human-centered approach, especially during the final selection steps, but also critical in providing a positive candidate experience, which most recruitment experts overwhelmingly favor in the recent studies.

The feasibility and effectiveness of such hybrid systems, which was required and improved in the circumstances of the COVID-19 pandemic, was proved by its practical implementation.

In the end, this framework proposal aims at achieving a perfect equilibrium. It takes advantage of the irrefutable efficiency benefits, data crunching capacity, and supposed bias minimization that technology promises, and protects the invaluable quality of human interaction, empathy, moral supervision and subtle judgment in the vital task of picking individuals to organizations.

6. Conclusion

According to the review, there is a clear indication of the possibility to map fields to search specific quantitative models of sustainability. Such models must be founded on thorough qualitative research of the concepts encompassing the contemporary meaning of corporate sustainability. One of such models is the one discussed above. The approach to stability analyses which is based on a set of ordinary differential equations offers numerous strengths which include the required information can be easily accessible within the organization. Upping to modern IT the information can be easily processed. It is not needed to solve the system to come up with the most appropriate values of the variables. To this end, an adequate method of defining the boundaries of system stability is the topological methods. It is on these grounds that the given model is a promising field in future research.

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Information Security Audit – an Objective Prerequisite for Improving the Cybersecurity of the Enterprise

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Abstract. The issue of auditing the information security of the enterprise is relevant at all phases and stages of its development. Improving information connectivity between business entities operating both in the country's economy and internationally, the use of various complex digital calculations in the operational and strategic management of the business, storing and accessing data in the cloud, and others, are objective prerequisites for cyber-attacks, various frauds, data theft, as well as for the emergence of various other short-term and long-term risks. The object of consideration is the information security audit system of the enterprise, and the subject - the elements of this system. The goal is to improve this system based on an analysis of the elements of the information security audit system, giving priority to cyber risk, its inclusion in the risk management system and assessment of the enterprise's cyber security.

Keywords. Audit, information security, analysis, cyber risk, cyber security

1. Introduction

The information security audit provides objective information on the effectiveness of the measures and controls developed and implemented by the enterprise against existing, emerging and potential threats. It should prove and confirm, on the one hand, that the main risks to the enterprise are identified, monitored, analyzed, controlled and managed, and on the other hand – that managers and employees responsible for IT security have the ability to recognize and respond promptly and adequately to new threats and risks.

The information from the analysis of the discrepancies found during the audit with the generally accepted guidelines and good practices in the field of information security of the enterprise is the basis for the development and taking of correct and timely decisions for both preventive and subsequent corrective actions. Based on the information about the gaps and vulnerabilities discovered during the information security audit, the enterprise has the opportunity to obtain better protection of its main assets, as in modern conditions both the significance and the value and the relative share of long-term intangible assets are increasing.

The purpose of an independent information security audit is to demonstrate to what extent the operational and strategic decisions, actions and specific methods and means of protecting the enterprise's data meet the objectives set by its leadership and management. A well-conducted information security audit helps to add value and increase the trust of parties external to the enterprise, while ensuring compliance with regulatory requirements and information security standards.

An information security audit involves an in-depth analysis of the physical and logical protection of assets and data, administration and access levels, information security policies, as well as ensuring business continuity and planning for actions in emergencies, disasters and accidents. At the time of the information security audit, the current state of the enterprise regarding data protection is assessed.

The audit methodology is based on a risk-based approach in accordance with the requirements of the International Professional Association for Information Systems Audit and Control (ISACA), whose activities are focused on the audit and assessment of information security of enterprises, using good practices for information security. The audit of the information security of the enterprise must meet the requirements specified in the standards for this: ISO/IEC 27001 (standard for information security management systems, which defines a model for building and requirements for the specified systems); PCI DSS (a set of standards for data security in enterprises carrying out payment card activities - accepting, processing, storing or transmitting payment card information, ensuring the protection of cardholder data from fraud and violations); COBIT (an IT governance and security framework that helps enterprises manage and control their information technology, aligning it with their business objectives. The framework is a system of best practices, principles, and tools to improve risk management, compliance with regulatory requirements, and assurance of the quality and reliability of enterprise information systems); NIST (National Institute of Standards and Technology - an agency of the US Department of Commerce whose mission is to promote American innovation and the industrial competitiveness of enterprises); OWASP (an online community that publishes open source information and resources on the Internet of Things, system software, and web application security), etc.

The information security audit, carried out in accordance with the requirements of international standards for this, is a guarantee of good management and ensures high competitiveness of the enterprise in the field of its activity in which it operates and will continue to operate as a going concern.

2. Nature of the audit and types of audits

In general, an audit can be defined as an independent examination and assessment of a person, organization (enterprise), system, process, project or product in order to determine whether it meets certain criteria or standards.

According to P. Iliev, "an audit is a set of all actions and control procedures performed by authorized control bodies aimed at collecting and analysing financial and non-financial information to assess the management of financial resources and reporting in the audited entity with a view to their improvement." [8, p.2]

In the International Standards on Auditing (ISA), the nature of an audit is defined as a systematic process in which a competent independent expert collects, analyses and evaluates information that is amenable to quantitative and qualitative assessment in order to express an opinion on the degree of compliance with previously determined criteria [7].

There are different types of audits. As P. Iliev points out, "depending on the pursued goals, tasks, objects, scope and bodies of implementation, there are rich in types and diversity of audits." [8, p.5] Due to the great diversity of audits, it is necessary to classify them according to appropriately selected criteria. For example:

A. First criterion - depending on the relationship between the subject and the object of the audit (existence of an employment-legal relationship between the enterprise and the entity performing the audit): internal and external audit.

B. Second criterion - depending on the nature and content of the audit: financial audit (an opinion is given on the reliability of the financial statements of the enterprises); performance audit; systems audit; compliance audit; audit of information systems and technologies; audit of the enterprise's information security; social audit; marketing audit; certification audit (a consistent, documented examination of the activities, processes and systems of the enterprise in order to ensure, through clear evidence, compliance with all

requirements set by the relevant ISO standard. The purpose of the audit is to obtain a valid certificate under a given Management System); energy audit (a detailed review of the energy consumption profile of a building or group of buildings, industrial activity or installation. The energy audit is the first step towards a complete ESG transformation that turns regulatory requirements into a competitive advantage for the enterprise), etc.

C. Third criterion. Depending on the type of audited activity: public sector audit; audit of insurance companies; audit of non-profit legal entities; audit of cooperatives; audit of political parties, etc. [8, p.6]

3. Audit of the enterprise's information security

The security of the information that is processed and stored in the enterprise, as well as of its information arrays, essentially represents protection against threats and various types of risks. This creates the need for permanent analysis and assessment of the enterprise's information security. Moreover, new types of threats and risks to the security of the information that is created in the enterprise or comes from external entities, functions, is used by the enterprise and is stored in its information arrays are constantly emerging. Based on the information obtained from the analysis, the weaknesses, vulnerabilities and gaps that may exist in the information network and/or information systems of the enterprise are revealed and identified. The comprehensive audit of the security of the information and information arrays of the enterprise covers many and in-depth policies and procedures in the modern conditions of constantly emerging various threats, risks and new vulnerabilities. In these conditions, audits must verify the scope of controls to ensure stable protection of data, information, information arrays of the enterprise and in general of the enterprise's information security management system. Moreover, the sustainable development of the enterprise implies and requires the implementation of additional costs to achieve sustainability in its three components (economic, social and environmental). The costs of cybersecurity of the enterprise, reflected at the first level as costs of economic elements, and at the second level - as administrative costs, have a direct impact on the financial results, and hence on the financial condition and financial stability of the enterprise.

It is necessary to note that the assessment of vulnerabilities is not limited to technology, but it is extended to the processes and people who are part of the information security ecosystem, and can be generalized to the cybersecurity of the enterprise.

4. Internal audit

In accordance with the provisions of the ISO 27001 standard, an enterprise can undergo internal and external audits to demonstrate that it adheres to current best practices for information security management.

An ISO 27001 audit is a systematic and independent examination of an enterprise's information security management system (ISMS) to determine whether it complies with this standard. The purpose of an information security audit is to verify whether the enterprise's ISMS meets the requirements of the ISO/IEC 27001:2022 standard, the latest version of which is 2022, and on this basis to assess the effectiveness of the system and identify opportunities for its improvement.

An internal audit is a review of the enterprise's ISMS carried out by internal personnel, with an employment relationship between the audited enterprise and the personnel performing the audit. It is possible for an internal audit to be performed by an external contractor hired to work with an internal team, in which case the audit of the enterprise's information security is considered an internal audit. Even when an internal

audit is performed by an external party, it is considered an internal audit. The exception to this is when the external auditor is part of an ISO 27001 certification body, and the audit is classified as an external information security audit.

The internal audit of the enterprise's information security management system (ISMS) covers the following stages:

- 1) a review of the current IT processes and the scope of the enterprise's ISMS;
- 2) a review of the internal documentation regarding the ISMS policies and procedures, as well as the organization for its maintenance in the enterprise;
- 3) an analysis and assessment of the risk and weaknesses of the enterprise's ISMS;
- 4) review and study of evidence from the enterprise's activities that identify whether the policies and procedures of the ISMS are applied in their logical sequence and interconnectedness;
- 5) comparative analysis of the information from the review of internal documents on the ISMS policies and procedures and the requirements contained in the ISO 27001:2022 standards;

6) based on the findings made during the information security audit, development and implementation of improvements regarding its ISMS in the enterprise's activities.

The enterprise should develop and consistently implement an internal audit program in order to maintain compliance with the requirements of the ISO 27001 standard (see clause 9.2 of the standard), which should determine and record: the frequency of internal audits; the methods that will be used when conducting internal audits; the persons responsible for planning, conducting, completing and reporting the results of internal audits of the enterprise's ISMS. We consider it appropriate to point out that it is appropriate to conduct an internal audit of the ISMS at least once a year, for example, towards the end of the current reporting period, which should be tied to the preparation of the company's annual financial statements.

5. External Audit

On the issue of external audit of the enterprise's information security, we will focus our attention on three important areas:

- certification audits according to ISO 27001 standards;
- audits according to the Personal Data Protection Regulation;
- audits according to the Network and Information Security Directive.



Fig. 1. ISO Standards 27001:2022

The new ISO 27001:2022 framework (effective October 2022 – see Figure 1) adds 11 new controls that compliant enterprises must implement in their practices. Some of the new areas included in the audited controls are:

- Threat intelligence and continuous risk management;
- Cloud information security;
- Business continuity from a communications systems perspective;
- Physical security monitoring;
- Configuration management;
- Deletion of sensitive data;
- Appropriate data masking (anonymization);
- Web and content filtering;
- Use of secure encryption principles.

Enterprises interested in ISO 27001 certification should undergo four external audits:

1) ISMS design review (the auditor reviews the enterprises documentation, processes and procedures in order to express an opinion and ensure that the controls and design of the information security management system comply with ISO 27001 standards;

2) certification audit (the auditor reviews the business processes and controls in the enterprises in order to ensure that they meet the requirements of ISO 27001);

3) surveillance audits (the auditor performs periodic (surveillance) audits of specific areas of the enterprises information security management system in order to express an opinion and ensure that it implements the procedures and processes defined and recorded in its internal documents concerning this system);

4) recertification audits (carried out every three years and covering all areas of the enterprise's information security management system, providing guarantees that it continuously follows the requirements of the ISO 27001 standards and improves its security system when new risks arise regarding information and its information arrays.

In order to process the personal data of their employees, as well as of external entities related to their activities, enterprises must have a legal basis for this. They should develop and implement in their activities a system of actions and processes that will become a quality and effective audit model under the General Data Protection Regulation. At the same time, each enterprise should organize continuous monitoring and improvement of the audit model by developing a system of appropriately selected measurable indicators that lend themselves to maturity modelling. The above gives rise to the significance, importance and relevance of the issue of auditing under the General Data Protection Regulation (see Figure 2).

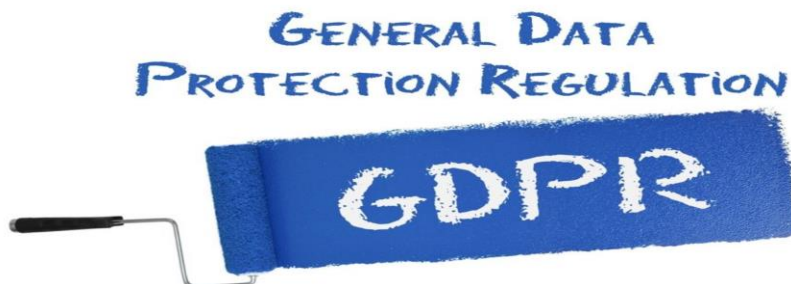


Fig. 2. GDPR Directive - General Data Protection Regulation

The audit under the data protection regulation provides assurance to both the enterprise itself and its business partners, as well as to the state and municipal administration, that it has complied and continues to comply with the requirements of the regulation on the protection of personal data of individuals with regard to their processing and their free movement.

The regulation also applies to entities located outside the European Union and the European Economic Area, but which process data of citizens of the European Union member states. The main objective of the general regulation is to guarantee to citizens that, in implementing continuous and effective control over their personal data, both compliance gaps and risks (current and potential) for the enterprise are permanently identified, by developing and implementing appropriate measures to eliminate them in its activities.

On 16 January 2023, the Network and Information Security 2 (NIS 2) Directive on measures to achieve a high common level of cybersecurity in the European Union (NIS2 Directive) and the Directive on the Resilience of Critical Entities (CER Directive) entered into force. The NIS2 Directive repeals the existing NIS Directive, creating a more comprehensive and harmonised system of cybersecurity rules for enterprises operating in the Member States of the European Union. The CER Directive repeals the European Critical Infrastructure Directive and introduces new, stricter rules for the cyber and physical resilience of critical companies, structures and networks. The NIS2 Directive is the first piece of pan-European legislation on cybersecurity for enterprises operating within the European Union. The aim of the NIS2 Directive is to achieve a high common level of cybersecurity in the Member States of the European Union.

H. Stanev points out that "a study for the period June 2021 - June 2022, cited by the European Union Agency for Cybersecurity (ENISA), identifies eight main threats to cybersecurity in the EU:

- Ransomware - taking control of data on a given device with a subsequent request to pay a certain amount in order to restore access to the data;

- Malware - through computer viruses, worms, Trojan horses and spyware, a system is penetrated to be used for other purposes (e.g. cryptojacking (secret use of processing power to create cryptocurrencies) or gaining control over cameras or routers);

- Exploiting human errors - about 60% of system breaches in Europe, the Middle East and Africa (Internet address from <https://www.europarl.europa.eu/topics/bg/article/20220120STO21428/kibersighurnost-ghlavnite-i-novite-zaplakhi>) are related to the use of human errors by misleading users and opening a dangerous file or visiting an insecure website, unauthorized access to computer systems or data is provided. Most often, such attacks begin with sending an email ("phishing") or text messages ("smishing") that appear to be sent by official financial institutions (banks);

- Threats to data (Threats to data) - methods such as Ransomware, Malware, Phishing, breaches (intentional attacks) or leaks (unintentional release) of data are used;

- Threats to the availability of data or services interrupting users' access to their information resources by overloading the network infrastructure or damaging the system (so-called Denial of Service (DoS) attacks, Distributed Denial of Service (DDoS) attacks, Ransomware or Hardware failures);

- Threats to internet access (Threats to internet access) - taking control or destroying the internet connectivity infrastructure (again through Denial of Service (DoS) attacks, Distributed Denial of Service (DDoS) attacks, Network outages or Government censorship);

- Disinformation and propaganda (Disinformation and propaganda) by creating fake images, videos or audio recordings that are difficult to distinguish from the real ones (e.g. bots impersonate real public figures and send numerous fake comments);

- Supply chain attacks - interference in business relationships between suppliers and customers, by simultaneously attacking to obtain economic benefit (inviting payment on a real invoice but on the account of a third party) or attempting to worsen the relationship between them (so-called Inserting malicious code, compromising third-party services or Exploiting vulnerabilities).” [9, p.1041]

The cybersecurity audit should focus on the basic rules that the enterprise should apply during its activities in order to build sustainable protection against modern threats, which are showing a tendency to diversify, deepen and become more difficult to recognize. These rules can be reduced to:

- 1) strengthening systems by eliminating unnecessary services, which aims to reduce the possibilities for cyberattacks;
- 2) access management - applying the principle of least privilege and two-factor authentication;
- 3) network protection - segmentation, TLS inspection, providing important improvements such as improved speed and encryption, as well as data traffic monitoring;
- 4) constant real-time monitoring and incident analysis using AI-based tools;
- 5) sustainable archiving - regularly testing and maintaining backups located outside the main networks.

The audit stages in accordance with the Network and Information Security Directive 2 (NIS 2) can be presented in the following sequence and relationship between them:

- 1) assessment of the degree of usefulness of network and information security measures;
- 2) identification of weak points and assessment of the riskiest ones;
- 3) implementation of improvements, with information about this being disclosed in a timely manner;
- 4) linking the indicators for measuring cybersecurity with real business indicators, such as the degree of vulnerability, response time, security improvement;
- 5) verification of privileged accounts and protection of administrator and accessible profiles;
- 6) verification of the personnel who introduce and promote the use of good practices in each department of the enterprise;
- 7) verification of the current state of the enterprise, the place it occupies in terms of network and information security and establishment of the necessary actions to achieve full sustainability of the protection of the enterprise's information and information arrays;
- 8) organizing constant monitoring and vulnerability scanning;
- 9) building a system for regular vulnerability scanning, access management and backup storage in order to achieve sustainable protection.

In our opinion, an enterprise's cybersecurity issues should be integrated into its mission, vision, and strategy (see Figure 3).



Fig. 3. Integrating information security auditing into enterprise strategy

6. Stages of the enterprise information security audit

The enterprise information security audit is a system of elements between which there are objective relationships and dependencies. One of the elements of this system is the stages in conducting the information security audit and the enterprise information security management system. The stages of the audit can be systematized in the following sequence: preparatory stage; implementation; reporting; results.

1) *First stage. Preparatory stage.*

During the preparatory stage, the following activities are carried out:

Activity 1. Audit planning.

When planning the audit, its goals and objectives are determined, through the solution of which the goals can be achieved. The goals and objectives of the audit should be defined in an appropriate manner, be clearly and precisely formulated, be understandable, measurable, achievable and lead to the achievement of the results desired by the management. They should cover all the main areas of the enterprise's information and technical infrastructure. For example, the objectives of the audit may include compliance with regulatory requirements, including those for cybersecurity, assessment of network security, disclosure of potential weaknesses and vulnerabilities in the software and hardware used by the enterprise, and others. Also, when planning the audit, training of the enterprise's employees (staff) should be carried out on best practices in the field of cybersecurity and the protection of its information arrays and systems. In conclusion, it should be noted that the prepared plan for conducting an IT security audit should be approved by the company's management.

Activity 2. Formation of an audit team.

This activity involves the formation of an audit team of highly qualified and experienced professionals in various aspects of IT security, such as network security specialists, system administrators and compliance experts, etc. During this activity, a preliminary meeting of the audit team should be organized, at which it should be introduced and the main strategies, goals and objectives adopted by the enterprise in the field of IT security should be discussed. At this meeting, the tasks, responsibilities and deadlines for implementation should be distributed to each of the members of the audit team.

Activity 3. Audit Information Assurance.

This activity is related to the collection of the necessary documentation, formation and description of the enterprise's policies, concerning and related to the enterprise's IT infrastructure. These include network diagrams, system configurations, security policies,

access control and incident response plans. The information contained in the enterprise's current documentation and policies is of great importance in providing complete and comprehensive data on the state of its IT security. Based on this information (audit information assurance), the audit team has the opportunity to conduct an in-depth analysis and assessment of the security of the enterprise's IT infrastructure.

Activity 4. Benchmarking and assessing compliance with security standards and regulations.

This activity should assess the compliance of the enterprise's policies with applicable standards and regulations in the field of IT security. Failure to comply with the requirements can lead to large fines, damage to the reputation of the enterprise and deterioration of its financial results, condition, stability and competitiveness. During the IT security audit, compliance with regulatory requirements in this area should be assessed, as well as the possible potential risks associated with their non-compliance.

Activity 5. Conduct Vulnerability Assessments and Penetration Testing.

Vulnerability assessments and penetration testing help auditors uncover weaknesses in networks, systems, and applications. Vulnerability assessments involve scanning IT infrastructure to detect security gaps, while penetration testing simulates real-world cyberattacks. The goal is to provide an assessment of an enterprise overall security resilience and security controls, providing valuable insight into areas that require improvement in their security posture.

Activity 6. Analysis of access control and user permissions.

This activity includes a detailed review, permanent and comprehensive control of access and user permissions for access to user information systems. The goal here is to determine whether only authorized persons have access to sensitive information in the enterprise. During this activity, it should be determined whether the principle of least privilege is observed, in accordance with which the enterprise should provide users with the minimum level of access that is necessary and sufficient to perform their job functions. Along with this, it is necessary to assess the enterprise's policies for maintaining passwords and their timely updating, as well as multi-factor authentication and processes for revoking access to information systems, with which the enterprise is able to protect itself from unauthorized access. Therefore, activity's 6 are aimed at reviewing, critically analysing and optimizing access control measures to information arrays and systems in order to ensure reliable security for them.

Activity 7. Review of physical security measures.

Observations in practice show that in most enterprises the issue of physical security of information arrays and systems is neglected, even when conducting an IT security audit. It should be noted that the review of physical security measures is important and they are crucial for protecting sensitive equipment and information from unauthorized access, theft and damage. The activities here include a thorough and comprehensive review of the security measures implemented on the premises of the enterprise, including access control systems, security cameras and protected server rooms.

Activity 8. Assessment of incident response and disaster recovery plans.

During this activity, a review of the enterprise's incident response and disaster recovery plans is carried out as part of the IT security audit. A well-prepared response plan allows to minimize potential impacts and breaches in the enterprise's IT security. At the same time, a reliable disaster recovery plan helps and enables the rapid restoration of the enterprise's operations after data loss. Particularly important in modern conditions is the permanent and

reliable assessment of the enterprise's existing plans in order to promptly identify areas for improvement, to recommend the use of best practices, by adopting quick and effective measures for adequate responses to incidents related to the enterprise's cybersecurity.

Activity 9. Identification, analysis and assessment of the risk associated with the main activities and assets (resources) of the enterprise, on the basis of which the IT security audit will be conducted.

2) Stage 2. Execution.

During the implementation of the enterprise's IT security audit, the following activities are performed:

Activity 1. Assessment of the effectiveness of the controls used in the enterprise to achieve information security.

Activity 2. Assessment of the enterprise's communication and network security.

Activity 3. Assessment of the security of the main and web-based applications used by the enterprise during its activities.

Activity 4. Assessment of the security of the enterprise's databases.

Activity 5. Assessment of the security of the main server complexes and the services provided by them in carrying out the enterprise's business.

Activity 6. Analysis and assessment of the methods used for security of endpoints and individual workstations in the enterprise.

Activity 7. Scanning for vulnerabilities and potential threats to the security of information of the Internet-accessible systems and applications that the enterprise uses in carrying out its business.

3) Stage 3. Reporting. During this stage, a comprehensive and final report is prepared and presented, covering all findings made during the audit of the enterprise's IT security, including the identified possible measures to improve the security of its information arrays and systems.

4) Stage 4. Result. The final report on the audit of the enterprise's IT security includes a detailed description of the conclusions after the analyses and assessments of security on the individual systems. As a supplement to the report, recommendations for improving security and optimizing the enterprise's information environment are also indicated.

7. Conclusion

The benefits for the enterprise from a fully performed IT audit of its information security can be systematized in the following directions:

1. A competent and qualitatively prepared analysis of the current state of the enterprise's information security provides the basis on which to plan and ensure better and timely active protection of its key information assets.

2. The recommendations made during the audit and the application of a systematic approach allow for the identification and prioritization of the necessary changes in the design, planning and budgeting of the enterprise's information infrastructure activities.

3. Based on the final report from the audit, a specific work program is drawn up to improve information security, taking into account the gaps and vulnerabilities found in the communication and information systems used by the enterprise.

4. The audit creates the prerequisites for achieving fuller compliance with both good practices and regulatory requirements in the field of information security of the enterprise.

5. The actions taken to eliminate the gaps identified by the audit regarding the enterprise's information security help maintain more reliable communication with all parties interested in its activities, as well as improve security when working with partners and other enterprises and organizations.

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Economic Metrics for Measuring the Effectiveness and Efficiency of Cybersecurity Investments

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Abstract. In an era of escalating cyber threats, organizations face the persistent challenge of justifying and optimizing financial allocations toward cybersecurity. This paper addresses this challenge by presenting a comprehensive framework of economic metrics designed to measure the effectiveness and efficiency of cybersecurity investments quantitatively. Moving beyond technical assessments, the study grounds itself in financial and risk-based models to provide a business-centric evaluation of security initiatives. The methodology systematically outlines key quantitative tools, including Total Cost of Ownership (TCO) for assessing long-term investment value, Single Loss Expectancy (SLE) and Annualized Loss Expectancy (ALE) for quantifying cyber risk in monetary terms, and Return on Security Investment (ROSI) for evaluating the financial return of security controls. Furthermore, the analysis incorporates capital budgeting techniques such as Net Present Value (NPV) to account for the time value of money in multi-year security projects. The results demonstrate that the integrated application of these metrics enables organizations to transition from qualitative security assessments to data-driven decision-making. This allows for the direct comparison of alternative security solutions, the objective justification of security budgets to stakeholders, and the strategic alignment of cybersecurity posture with overarching business objectives. The discussion acknowledges the inherent difficulties in estimating parameters, such as threat probability, but concludes that a disciplined, metric-driven approach is indispensable for rational resource allocation. By adopting this economic perspective, organizations can not only enhance their security resilience but also demonstrate tangible value and fiscal responsibility, thereby transforming cybersecurity from a perceived cost center into a strategically managed business function.

Keywords: Cybersecurity Economics, Return on Security Investment (ROSI), Annualized Loss Expectancy (ALE), Total Cost of Ownership (TCO), Net Present Value (NPV), Risk Quantification, Security Metrics, Cybersecurity Investment, Economic Efficiency, Cyber Risk Management.

1. Introduction

!!!Disclaimer: This publication does not constitute legal or economic advice. The values used are hypothetical and may vary depending on the object, subject matter, and context, as well as the possible values of different service providers. It should be noted that the result will not always be positive, as in the scenario shown.!!!

In the contemporary digital landscape, characterized by pervasive connectivity and an ever-expanding attack surface, cybersecurity has transcended its traditional role as a technical IT function to become a cornerstone of organizational resilience, economic stability, and strategic governance. The relentless evolution of cyber threats - from financially motivated ransomware syndicates to state-sponsored espionage campaigns - poses a clear and present danger to businesses, governments, and critical infrastructure worldwide. As organizations

increasingly digitize their operations and assets, the potential financial, operational, and reputational damage from cyber incidents has reached unprecedented levels. The global economic impact of cybercrime is projected to soar into the trillions of dollars, underscoring a systemic risk that demands a proactive and strategically aligned response.

However, despite this universal recognition of cyber risk, Chief Information Security Officers (CISOs) and security leaders continue to grapple with a fundamental and persistent challenge: justifying cybersecurity budgets and demonstrating their value to executive leadership and board members. Cybersecurity investments are often perceived as a "cost center"—a necessary expense with an intangible return, rather than a value-driven investment that contributes positively to the organization's strategic objectives. This perception gap stems from the inherent difficulty in quantifying what did not happen due to successful security interventions. Unlike a new sales platform that can be measured by revenue growth, the success of a security control is often measured by the absence of loss, creating a significant hurdle for effective communication and resource allocation.

This communication gap is frequently bridged with technical jargon and fear-based appeals, which are increasingly ineffective in a competitive business environment defined by rigorous financial scrutiny and accountability. Executive decision-makers, trained to evaluate investments based on Return on Investment (ROI) [1], Net Present Value (NPV) [2], and Total Cost of Ownership (TCO) [3], require a financial and economic lexicon to understand and approve security initiatives. The inability to translate technical security postures into business-relevant financial terms can lead to underinvestment, the misallocation of resources, and an overall security posture that is misaligned with the organization's actual risk appetite and business strategy.

To address this critical gap, the field of cybersecurity economics has emerged as a vital discipline. It provides a framework for applying well-established economic principles and financial metrics to the domain of information security. This paradigm shift moves the conversation from "how secure are we?" to "how much security is economically efficient?" and "what is the optimal level of investment in cybersecurity?". It acknowledges that perfect security is an unattainable and economically irrational goal; instead, the objective is to manage cyber risk to a level that is acceptable to the business, ensuring that every dollar spent on security delivers the maximum possible reduction in expected loss.

This paper aims to contribute to the evolving discipline by synthesizing and presenting a comprehensive framework of key economic metrics specifically designed to evaluate the effectiveness and efficiency of cybersecurity investments. The primary objective is to equip security professionals and decision-makers with a practical, quantitative toolkit for strategic planning and justification. The research question central to this work is: How can a defined set of economic metrics be systematically applied to measure and communicate the value and performance of cybersecurity programs?

To answer this question, this paper is structured as follows. The subsequent Methods section will provide a detailed exposition of the core economic models, including Total Cost (TC) for program budgeting, Total Cost of Ownership (TCO) for lifecycle analysis, and risk quantification metrics such as Single Loss Expectancy (SLE) and Annualized Loss Expectancy (ALE). It will further delve into investment appraisal techniques, namely Return on Security Investment (ROSI) and Net Present Value (NPV), which are crucial for comparing alternative security solutions and justifying capital expenditures. The Results section will illustrate the practical application of these metrics, demonstrating how they can be used to calculate risk savings, net savings, and ultimately, a financially sound ROI for security projects. The Discussion will address the practical challenges and limitations of these models, particularly concerning data quality and estimation uncertainty, while arguing for their indispensable role

in modern, risk-based cybersecurity management. Finally, the Conclusion will summarize the findings and reaffirm the necessity of integrating economic analysis into the core of cybersecurity governance, thereby transforming cybersecurity from a technical safeguard into a strategically managed business enabler.

2. Methodology

The following economic metrics were analyzed based on established financial and risk assessment methodologies.

2.1 Total Cost (TC)

The total cost of a cybersecurity program as a project can be defined as:

$$TC = I_{new} + OC_{new} + OC_{call} \dots \quad (1)$$

where,

TC – total costs;

I_{new} - research and investment costs,

OC_{new} - ongoing operational costs;

OC_{call} - the costs of maintaining legacy systems until their retirement [4].

2.2 Annualized Loss Expectancy (ALE)

ALE estimates the expected loss from an asset over one year and is calculated as [5]:

$$ALE = ARO \times SLE \dots \quad (2)$$

where,

ALE - expected loss from an asset over one year;

ARO - Annual Rate of Occurrence;

SLE - Single Loss Expectancy.

“Annualized Rate of Occurrence, also known as ARO, refers to the expected frequency with which a risk or a threat is expected to occur. ARO is also commonly referred to as Probability Determination.” [6].

“Single Loss Expectancy (SLE) is defined as the cost of a single loss, calculated by multiplying the Asset Value (AV) by the Exposure Factor (EF).” [7].

2.3 Single Loss Expectancy (SLE)

SLE quantifies the monetary loss expected per risk occurrence:

$$SLE = AV \times EF \dots \quad (3)$$

where,

AV - the Asset Value;

EF - Exposure Factor.

2.4 Total Cost of Ownership (TCO)

TCO includes both the purchase price and operational costs of an asset over its lifecycle. It provides a long-term perspective on the value of security investments [8].

2.5 Return on Security Investment (ROSI)

ROSI measures the financial return of security investments by comparing the cost of the investment to the risk reduction achieved:

$$ROSI = \frac{\text{Risk Savings} - \text{Security Investment}}{\text{Security Investment}} \times 100\% \dots \quad (4)$$

2.6 Net Present Value (NPV)

NPV can evaluate the profitability of a security investment over time:

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \dots \quad (5)$$

where,

C_t -net cash flow during period;

C_0 - the initial investment;

r -the discount rate;

T - number of periods.

2.7 Expected Annual Risk Cost

This metric aggregates the expected cost of all threats

$$\text{Expected Annual Risk Cost} = \sum (\text{Threat Probability} \times \text{Potential Loss}) \dots \quad (6)$$

2.8 Risk Savings and Net Savings

Risk Savings are calculated as:

$$\text{Risk Savings} = \text{Total Base Risk} \times \text{Risk Reduction Rate} \dots \quad (7)$$

Net Savings are derived from:

$$\text{Net Savings} = \text{Total Risk Savings} - \text{Total Cost} \dots \quad (8)$$

2.9 ROI Based on Net Savings

The final ROI is calculated:

$$ROI = \left(\frac{\text{Net Savings}}{\text{Total Cost}} \right) \times 100\% \dots \quad (9)$$

3. Results

This section presents a comprehensive application of the economic metrics outlined in the Methods section to a hypothetical scenario with the implementation of a Security Information and Event Management (SIEM) system. The analysis will demonstrate the step-by-step calculation of each metric and its interpretation for decision-making.

3.1 Scenario definition and Base assumptions

The scenario: *A company processes sensitive customer data and is subject to stringent regulatory requirements. The existing security infrastructure lacks centralized monitoring, leading to a high risk of undetected data breaches. The proposed SIEM solution is projected to have a lifespan of five years. For the scenario, we have two hypotheses: 1) Assumption without SIEM and 2) Assumption with SIEM.*

The first step is to define values for Base Risk Assumptions (Without the SIEM). “Risk Assumption is a risk management tool where a company chooses to make itself responsible for potential losses, such as not obtaining insurance due to minimal risk of loss or opting for self-insurance by setting aside funds for future losses.”[9]

- **Asset Value (AV) of Protected Data:** \$5,000,000;
- **Threat:** Major data breach via an undetected advanced persistent threat (APT). An advanced persistent threat (APT) is a sophisticated, sustained cyberattack in which an intruder establishes an undetected presence in a network to steal sensitive data over a prolonged period. An APT attack is carefully planned and designed to infiltrate a specific organization, evade existing security measures, and fly under the radar.”[10]
- **Exposure Factor (EF):** 40% (estimation of data loss and exposure);
- **Single Loss Expectancy (SLE):**
 - **Annual Rate of Occurrence (ARO):** 20% (a 1-in-5-year probability of a significant breach);
 - **Annualized Loss Expectancy (ALE - Base):** This \$400,000 represents the expected annual cost from this specific threat in the current, unimproved state.

The second step is to define values for Investment Cost Assumptions (For the New SIEM).” Security information and event management, or SIEM, is a security solution that helps organizations recognize and address potential security threats and vulnerabilities before they have a chance to disrupt business operations.”[11]

- **Initial Setup Cost (I_{new}):** \$150,000 (includes software licenses, hardware, and initial configuration).
- **Annual Operational Cost (OC_{new}):** \$50,000 (includes maintenance, tuning, and dedicated analyst time).
- **Project Lifespan (n):** 5 years.
- **Discount Rate (r):** 8% (reflecting the company's cost of capital).” Cost of capital is the minimum rate of return or profit a company must earn before generating value. It's calculated by a business's accounting department to determine financial risk and whether an investment is justified.”[12]

3.2 Application of Economic Metrics

Total Cost of Ownership (TCO). The TCO provides a realistic picture of the total financial commitment over the system's lifespan, moving beyond the mere purchase price. The TCO of the SIEM solution is \$400,000. This figure is essential for budgeting and is a key input for subsequent ROI and NPV calculations.

Risk Reduction and Risk Savings. The primary value of the SIEM is its ability to reduce risk. It is estimated that the SIEM will enhance threat detection and response, thereby reducing the likelihood of a successful major breach. **Post-SIEM ARO** is reduced from 20% to 5%.

Post-SIEM ALE - Risk Reduction Rate is 75%. The monetary value of this risk reduction is the Risk Savings. The SIEM investment is expected to generate \$300,000 in annual risk savings by significantly lowering the expected annual loss from data breaches.

Net Savings and Return on Investment (ROI). Net Savings and ROI translate risk reduction into direct financial performance indicators. Over five years, the SIEM project yields net savings of \$1.1 million and an impressive ROI of 275%. This provides a powerful, easily understandable argument for the investment, demonstrating that for every dollar spent, the company expects a return of \$2.75 in saved losses.

Net Present Value (NPV). While ROI is beneficial, NPV offers a more sophisticated analysis by taking into account the time value of money. It discounts future cash flows (in this case, the annual risk savings) to their present value. The annual net cash flow (C_t) is the risk savings minus the yearly operational cost: $\$300,000 - \$50,000 = \$250,000$. Note that the initial cost (C_0) is \$150,000. The NPV is strongly positive at \$848,177. A positive NPV indicates that the projected earnings (in terms of risk savings) generated by the investment exceed the

anticipated costs, when considered in present-value terms. This makes the SIEM project a financially attractive and value-adding initiative.

Return on Security Investment (ROSI). ROSI offers a security-specific variant of ROI, focusing purely on the efficiency of the security spend itself. The annualized security investment is the TCO divided by the project lifespan: $\$400,000 / 5 = \$80,000$. The ROSI of 275% confirms the high efficiency of the investment from a security-centric viewpoint, aligning with the classic ROI calculation and providing a consistent narrative of substantial value.

The results are summarized in Table 1.

Table 1. Summarised results.			
<i>Metric</i>	<i>Formula</i>	<i>Result</i>	<i>Interpretation</i>
Base ALE	$SLE \times ARO$	\$400,000	Expected annual loss without the new SIEM.
TCO	$I_{new} + (OC_{new} \times n)$	\$400,000	Total lifecycle cost of the SIEM investment
Risk Savings	$ALE_{base} - ALE_{new}$	\$300,000/yr	Annual monetary benefit from reduced risk.
Net Savings	$(RiskSavings \times n) - TCO$	\$1,100,000	Total net financial benefit over 5 years.
ROI	$NetSavings / TCO \times 100\%$	275%	High overall return on the invested capital.
NPV	$\sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0$	\$848,177	The investment adds significant present value.
ROSI	$\left(\frac{Net\ Savings}{Total\ Cost} \right) \times 100\%$	275%	The security spending itself is highly efficient.

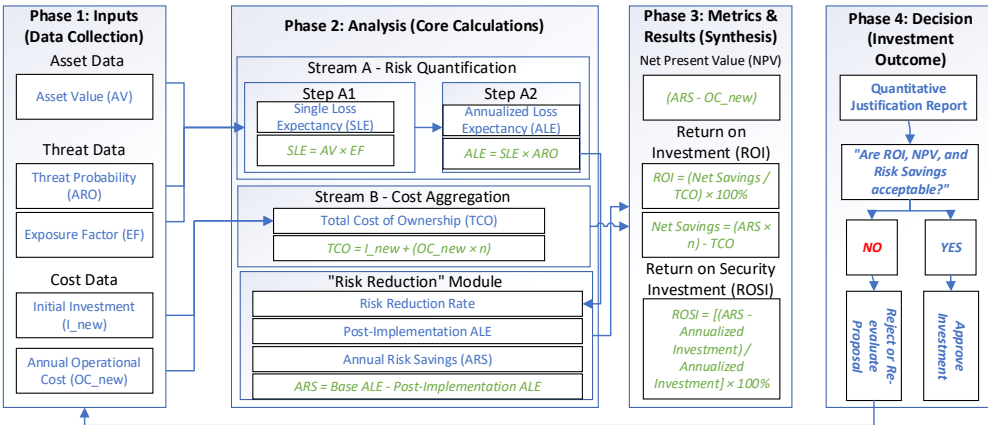
The results uniformly and strongly indicate that the proposed SIEM investment is economically justified. It transitions the justification from a qualitative, fear-based argument ("we might get hacked") to a quantitative, business-centric case, demonstrating substantial risk reduction, a positive net present value, and a high return on investment. This multi-faceted economic analysis provides management with the robust financial data needed to approve the project confidently.

4. Discussion

The comprehensive results from the SecureFin case study demonstrate the powerful utility of economic metrics in cybersecurity decision-making. The uniformly positive outcomes—a 275% ROI, \$848k NPV, and \$300k in annual risk savings—present a compelling financial case for the SIEM investment. However, **the actual value of this analysis lies not merely in the positive numbers but in the more profound insights, limitations, and strategic implications that these metrics reveal.**

This discussion interprets these results, addresses the challenges of quantitative risk assessment, and explores the organizational shift required to leverage such frameworks effectively.

Figure 1: Graphical Process Model for Cybersecurity Economic Evaluation



Interpretation of Economic Outcomes

The first and most direct interpretation of the results is that the SIEM investment is not a cost, but a value-generating activity. The substantial positive NPV indicates that the project is expected to increase the value by over \$848,000. This aligns the cybersecurity initiative with capital projects in other parts of the business, such as new manufacturing equipment or market expansion, which are also evaluated on their value-creation potential. The high ROI and ROSI further reinforce this, showing that the capital allocated to security can compete with, and even outperform, other potential investments within the organization. This fundamentally reframes the conversation for the board and CFO, moving cybersecurity from an operational expense to be minimized to a strategic investment to be optimized.

Furthermore, the decomposition of value through metrics like Risk Savings (\$300,000/year) and ALE provides critical granularity. It allows security leaders to move beyond vague statements about "improving security" and instead articulate a precise narrative: "This investment specifically addresses a \$400,000 per year data breach risk, and we are reducing it by 75%." This level of specificity is crucial for prioritization. Suppose another proposed control, such as an endpoint detection and response (EDR) system, claims to address a different threat with an ALE of only \$50,000. In that case, the organization can now make an informed, data-driven decision on where to allocate limited resources first.

The Critical Role of Assumptions and Data Quality

The robustness of this entire economic model is entirely contingent on the accuracy of its underlying assumptions. The results, while compelling, are a direct function of the estimated ARO (20% reduced to 5%), the Exposure Factor (40%), and the Asset Value (\$5 million). These figures are often the most challenging to derive with high confidence.

The ARO, in particular, is notoriously difficult to pin down. It is often extrapolated from industry reports, historical internal incident data (which may be incomplete), or expert opinion. A slight change in this assumption can dramatically alter the outcome. For instance, if the base ARO were only 10% instead of 20%, the base ALE would be \$200,000, and the annual risk savings would drop to \$150,000. This would lower the NPV to approximately \$299,000 and the ROI to 87.5%, still positive but significantly less compelling. This sensitivity underscores the necessity of conducting a sensitivity analysis or Monte Carlo simulation alongside the primary calculation to present a range of possible outcomes, rather than a single, potentially fragile, number.

Similarly, the Asset Value (AV) must reflect more than just the replacement cost of hardware or software. For a data asset, it should encompass regulatory fines, reputational damage, customer churn, operational downtime, and legal fees. Quantifying these intangible factors requires collaboration with leaders from legal, communications, and business units. The EF is another estimation that demands careful consideration; is 40% of the data asset truly exposed in a single breach? Refining these inputs through cross-functional workshops and leveraging industry frameworks, such as FAIR (Factor Analysis of Information Risk), can significantly enhance the model's credibility.

Strategic and Organizational Implications

Adopting an economic metrics framework necessitates a significant cultural shift within an organization. It requires the cybersecurity team to develop financial literacy and the finance team to develop a basic understanding of cyber risk. This collaboration is essential for validating assumptions and ensuring the model aligns with the organization's overall risk appetite and financial planning processes. The CISO's role evolves from a technical expert to a business leader who can articulate risk in the language of the boardroom.

Moreover, this approach champions the principle of **economic efficiency in cybersecurity**. It implicitly acknowledges that not all risks are worth mitigating and that the goal is optimal risk management, not risk elimination. The analysis might reveal that for specific low-ALE threats, the TCO of a proposed control exceeds the potential risk savings, making it an economically irrational investment. In such cases, the organization may rightfully choose to accept, transfer, or mitigate the risk through a less costly means. This disciplined, cost-effective approach prevents overspending on security and ensures that resources are allocated to areas of the highest business impact.

Limitations and Future Directions

While powerful, this methodology is not a panacea. Its primary limitation is its reliance on estimation and prediction. It cannot account for "black swan" events—high-impact, low-probability threats that fall outside of historical models. Furthermore, it can struggle to quantify the positive benefits of security beyond loss avoidance, such as enhanced customer trust or enabling secure digital transformation initiatives that generate new revenue.

Future work in this field should focus on improving the data foundations for these models. This includes the development of industry-specific data lakes for cyber incidents to inform more accurate ARO estimates and standardized methodologies for valuing digital assets. The integration of these economic models into automated security platforms could also enable real-time, dynamic risk assessment, allowing organizations to adjust their security posture and investments based on a continuously updated view of the economic threat landscape.

5. Conclusion

This paper has established a comprehensive framework for evaluating cybersecurity investments through the rigorous application of economic metrics. The analysis, grounded in the hypothetical but realistic case of SecureFin, demonstrates unequivocally that cybersecurity initiatives can be transformed from intangible costs into quantifiable, value-driven investments. By leveraging established financial concepts such as Total Cost of Ownership (TCO), Annualized Loss Expectancy (ALE), Net Present Value (NPV), and Return on Security Investment (ROSI), we have provided a replicable methodology for justifying security expenditures in the language of business: risk reduction, return on capital, and value creation.

The key conclusion from this research is that a metric-driven approach fundamentally bridges the communication gap between technical security teams and executive leadership.

The case study results—a 275% ROI and a positive NPV of \$848,177—present a compelling, data-driven narrative that surpasses fear-based appeals. This methodology allows Chief Information Security Officers to present cybersecurity not as a drain on resources, but as a strategic function that directly contributes to the organization's financial health and operational resilience. It enables informed prioritization, ensuring that limited resources are allocated to counter the threats that pose the most significant financial risk to the enterprise.

However, the efficacy of this model is entirely dependent on the accuracy and rigor of its inputs. The critical challenge remains the credible estimation of parameters, such as threat probability and potential loss. Therefore, the adoption of this framework must be accompanied by a commitment to enhancing data collection through cross-functional collaboration and the application of industry-standard risk quantification methodologies. Organizations must view this not as a one-time calculation, but as an ongoing process of refinement and validation.

Ultimately, the transition to an economics-based cybersecurity model represents a necessary maturation of the profession. It moves the discipline beyond technical controls and compliance checklists towards a sophisticated, business-aligned practice of risk management. By embedding these economic principles into their governance structures, organizations can make more rational investment decisions, optimize their security posture, and demonstrably prove that effective cybersecurity is not merely a defensive necessity but a definitive contributor to sustainable business growth and longevity.

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Utilizing Artificial Intelligence in Auditing and Investigations

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Abstract. The integration of Artificial Intelligence (AI) into auditing and investigation processes represents one of the most transformative developments in the field of corporate governance and financial oversight. This paper explores the increasing utilization of AI in auditing, its benefits, challenges, and implications for the future of assurance and fraud detection by performing an empirical review of the literature and other relevant sources. Recent reports indicate that approximately 39% of internal audit functions currently utilize AI, with adoption expected to rise significantly by 2026. Through the review of existing academic and professional literature, this study identifies the key technologies being implemented—such as machine learning, robotic process automation, and natural language processing—and assesses their impact on audit efficiency, fraud detection accuracy, and overall audit quality. Furthermore, it highlights the emerging risks associated with AI adoption, including data quality issues, lack of technical expertise, algorithmic bias, and ethical or regulatory uncertainties. The paper also discusses the evolution of traditional fraud models toward AI-driven environments, introducing the concept of the “AI Fraud Diamond,” which acknowledges the complexity and technical opacity associated with modern fraud schemes. The findings emphasize the need for robust governance frameworks, interdisciplinary collaboration, and the continuous development of auditor competencies to ensure that AI enhances rather than compromises the integrity and effectiveness of the auditing process. Based on the findings the AI is here to stay and its adoption will become wider and wider auditors and investigators will have to learn to adapt to the new dynamics set by AI.

Keywords. Audit, artificial intelligence, fraud detection.

1. Introduction

The Artificial Intelligence boom is an example of a technology breakthrough similar to the invention of the computer. Businesses have begun relying on AI more and more in their day-to-day operations. Although artificial intelligence is a relatively new phenomena in auditing a report by Protiviti [1] shows that about one in five finance organizations have achieved benefits related to cost and efficiency by utilizing AI. Moreover, AI can be used in most organizational units. Based on a recent Pulse report by the Institute of Internal Auditors [2] almost half of the internal audit functions have reported using some sort of AI in their processes, with 34% of the respondents currently prospecting future use of AI in their activities. A recent survey by Wolters Kluwer [3] indicates that 39% of internal auditors are currently utilizing AI in some capacity with an estimate of 41% intending to adopt AI in 2026. As with all new technologies the adoption of AI comes with some emerging risks. According to the 12th Annual Global Internal Audit Perspectives on Top Technology Risks survey [4] 59% of the respondents indicate the advanced AI systems as a significant risk in the next couple of years. Highest risks include but are not limited to security risks (hacking, data poisoning), privacy risks (rights & law violations) and operations risks such as systems errors or unexpected downtime. Authors such as Bankova [5] have foreseen and pointed out the

needed shift from traditional IT audit to cyber audit due to the increasing dependence on IT technologies.

2. Artificial intelligence in auditing & investigation process

Suyono et al. [6] provide an overarching review of how artificial intelligence can be integrated in the auditing process as well as outline some of the limitations of utilizing such in auditing. The authors have leveraged several major academic databases including but not limited to Scopus and Google Scholar, to screen a set of articles which can be selected for further analysis. Based on their findings auditors have used the following technologies – Machine learning (suitable for pattern recognition and fraud detection), Robotic Process Automation (suitable for data extraction, transaction testing) and Natural Language Processing (suitable for analyzing sets of unstructured data for outliers, red flags and other irregularities).

The authors further outline several challenges if using AI including:

- Data of insufficiently good quality which decreases the accuracy and effectiveness of the results provided.
- Lack of competency with AI, which impedes effective adoption
- Issue related to ethics, transparency and accountability in situations where concerns related to fairness, bias and accountability arise.
- Expected regulatory intervention and uncertainty due to expected standards and regulations around AI usage and audit evidence etc.

The authors stress the need of accepting guidelines and frameworks on the use of AI in the audit process as well as the need for further research on the results of AI implementation in those processes such as the effect on audit quality, fraud detection rates, false positives etc). It has to be noted that such guidelines and frameworks could start to be used in preventing other risks to the organizations such as cyberfraud. As Bankova [7] states “hackers are constantly developing their skills and are increasingly taking advantage of the fear, insecurity and naivety of the average user”. Such actors are likely to utilize AI to success in their goals as well making the detection of fraud harder for organizations.

Aitkazinov [8] explored the question of how Artificial intelligence tools and technologies can be integrated into auditing processes and increase their effectiveness and accuracy. Several areas are identified which can benefit from AI: automation of routine tasks, improved anomaly detection, real-time monitoring on processes and improved audit quality and risk assessment. The challenges identified by the author encompass several areas emphasizing the need of technical expertise and resources, algorithmic bias and the changing role of the auditor shifting to a more oversight-based activities requiring different mindset and skills. The author reaches the conclusion that businesses should invest in training the necessary staff in the best way to utilize AI in order to increase the AI literacy as well as stresses the need of collaboration between different parties in and outside organizations such as auditors, data scientists and oversight bodies to adopt frameworks and standards that ensure AI usage aligns with professional standards, judgement and ethical considerations. The author believes that the integration of AI tools has the potential to bring transformation to the audit practice due to the fact that it allows auditors to overcome traditional sampling methods (moving from sampling to full data analysis), improve the analysis performed and to reduce the time needed for mundane tasks.

Fedyk, A., Hodson, J., Khimich, N. et al [9] have analyzed the impact of Artificial intelligence and the impact on the quality of the audit. The results indicate that AI investment improves the quality with a 5% reduction in the likelihood of an audit misstatement and reduce audit fees (up to 0.9%). The authors also provide an overview of the employees that utilize AI

in the auditing sector- most of them being a young male with the majority being with technical background such as computer science or mathematics – most likely the skills needed to configure and use the AI tools properly. Last but not least is a significant rise in the AI talent in the recent years which signals higher and higher adoption of artificial intelligence utilization. Rafael Romero-Carazas et al [10] have conducted a literature review and bibliometric analysis in Scopus indicating that forensic auditing with the help of artificial intelligence have advanced enabling auditors to identify fraud faster and at an early stage and minimize the negative impact of fraud should it occur. The importance of identifying critical data is stated as well as the need of auditors to adapt to the advances in technology. Supriadi [11] has specifically examined the factor of Artificial Intelligence in detecting fraud in accounting audits. The conclusions of the author indicate and support the general consensus that AI can indeed improve not only the efficiency but the accuracy in detecting fraud. One of the main challenges posted by the author is the barriers of acceptance of AI in the accounting industry.

Fraud, investigation models and methodologies have been impacted as well by Artificial Intelligence. Traditional models like the fraud triangle have evolved. Zweers, B et al [12]. Have acknowledged that due to the technical advancements fraud has increasingly been depended on IT/AI systems and introduced the so called “AI fraud Diamond” which further develops the fraud triangle by adding a fourth element – technical opacity. The authors have used the traditional elements of Pressure (individual or organizational), Opportunity (process gaps and insufficient controls) and Rationalization (what is accepted internally) and shown how those manifest in environment where artificial intelligence exists. The fourth element – technical opacity- occurs when the environment is so complex and hard to understand that auditors and investigators cannot fully understand what is the situation. A variety of factors can lead to the technical opacity including but not limited to: constrained access, or even not enough knowledge. The authors further distinguish several types of fraud related to AI which can be used as a basis for auditors and investigators those are: input data manipulation (source data alteration), model exploitation and evasion, algorithmic decision manipulation (algorithms predicated an outcome/results based on bias or some other factor), synthetic fraud (fake identities or information facilitated by deepfakes) and AI ethics fraud (transferring the decision making and responsibility to AI for mismanagement or bad decisions).

A logical last question would be on how to audit and provide assurance that the artificial intelligence Ojewale et al. [13] have argued that although there are many tools that exists currently for AI auditing those can appear to be inadequate due to the inability of the users to access the data governing the behavior of the AI systems and apply consistent and holistic standards to provide integrity of the audit.

3. Conclusion

Artificial Intelligence has begun to redefine the auditing and investigative landscape, transforming how organizations detect irregularities, manage risks, and ensure compliance. The literature and empirical evidence reviewed indicate that AI not only improves audit efficiency and reduces costs but also enhances the accuracy of fraud detection and the quality of audit outcomes. Technologies such as machine learning, robotic process automation, and natural language processing enable auditors to move beyond traditional sampling methods toward comprehensive, data-driven analysis.

However, the rapid adoption of AI introduces new layers of complexity—ethical, technical, and operational—that demand vigilant oversight and new skillsets within the auditing profession. Risks related to data integrity, algorithmic bias, privacy, and regulatory

uncertainty underscore the importance of establishing clear standards and ethical frameworks governing AI use. Moreover, the evolution of fraud typologies, as illustrated by the AI Fraud Diamond, reflects the growing sophistication of digital deception, requiring auditors and investigators to adapt their methodologies accordingly.

Ultimately, successful integration of AI into auditing depends on a balanced approach—leveraging its analytical power while maintaining human judgment, ethical rigor, and accountability. Continuous learning, interprofessional collaboration, and proactive governance are essential to harness the full potential of AI as a force for transparency, accuracy, and trust in the audit and investigation processes. More research will be needed on how the landscape evolves in the near future. The rate of change should be proportional to the amount invested and wider adoption of the Artificial intelligence in more and more process.

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Cybersecurity Risk Management and Threat-Led Penetration Testing for Financial Stability

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Abstract. Since the Covid-19 crisis and the following period in 2020-2022, the digital world has become standard in order to facilitate all spheres of human activity. The virtual environment leads also to saving resources. As a result, information technologies have evolved at an immediate pace and the financial sector, along with many other areas of activity, has increasingly begun to fuse into the digital space. The financial ecosystem evolved. However, in addition to this development, cyber threats in the financial operations and financial entities have also augmented, leading to the need to achieve a resilient and secure digital environment. This need has become a critical element for the functioning of the financial sector, even more so in terms of the interconnectedness of the financial system operators. This article focuses on the latest developments in relation to the measures to secure the proper functioning of the financial sector in the digital world and particularly on the threat led penetration testing designed to identify weaknesses and prescribe preventive measures for better operational resilience of the financial entities.

Keywords: Cybersecurity, cyber-attacks, cyber threats, threat-led penetration testing

1. Introduction

The world is changing at an incredible speed and the financial stability is of primary importance. In the past, we have evidenced that the consequences of the financial crises could have a devastating effect on the regular citizens' lives. The models nowadays for stronger financial Europe are more than ever repetitive. In the 2025 State of the Union address by the European Commission President von der Leyen during a plenary session in the European Parliament in September 2025, an annual speech that highlights the priorities of the work of the European Commission in the year to come, it becomes obvious that Europe is now developing in a new way. Many actions were proposed to support digital projects and transformations. The President indicated that "...we will massively invest in digital and clean tech" [1] and this way she revealed the forthcoming preparations for the digital euro, support for the European AI Gigafactories and other innovative ways to facilitate businesses and consumers for competitive (and independent) Europe.

In an international situation characterised by uncertainty, strong economic competitiveness and increasing levels of conflict, ensuring a secure virtual operating environment is essential for economic stability, especially in view of the interconnectivity and interdependence of the services. The activities of cybercriminals pose new hybrid risks to the economic stability. We are witnessing sabotage of undersea telecommunication cables, system disruptions in large banks and third-party suppliers, as well as increasing complexity of cyber-attacks and hacker skills. Joining up cyber protection efforts is essential since there is a growing need for international cybersecurity drivers. This should be accomplished at European/international and not only at national level.

Further to the development of the digital world, the international, European and national authorities focused attention on the risks of information and communication technologies (ICT). The recent trends in preserving cybersecurity include preventive measures to minimize the incidents, which could be increasingly influencing and modifying the financial sector. As part of the measures, in principle every 3 years threat lead penetration testing must be accomplished for the critical information technologies providers in the financial sphere. This is the exact focus of the current paper aiming to present the last tendencies in managing the cybersecurity aspects of the financial world.

2. The importance of addressing ICT risks

Nowadays, cyber threats are experienced daily and therefore the companies have to be resilient continuously. Recent statistics show that the world is facing over 2,200 cyberattacks per day. In the latest publication of the European Union Agency for Cybersecurity (eNISA) [2], it is reported that intrusion via ransomware is significant, phishing has become even an industry, and the AI has now its influence in the area. The number of high impact incidents has decreased whereas the diversified and continuous pressure targets to erode the resilience of the organisations.

Currently, the financial organisations are trying to find the balance between convenience (providing user friendly services to consumers), competition (several financial entities competing in the market, offering innovative services at low cost) and resilience (the ability of a financial entities/the financial sector as general to continue to carry out its tasks by anticipating and adapting to the threats and other relevant changes in the environment and by recovering from incidents). Obviously, this is one of the main managerial tasks nowadays.

Nowadays the number of high impact incidents decreases. Some of them are worth mentioning, however. Since the systems of the economic operators are entirely in digital format and this way they are also interconnected, an incident in one of the operators could have many implications for others. It becomes obvious that prevention measures must be in place to minimise and, as far as possible, avoid domino effect upon incident.

One clear example of massive implication for other entities is the case with Amazon Web Services (AWS) cloud services outage on 20 October 2025. AWS is a company providing internet-based cloud service connecting businesses and people using their applications or online platforms. Businesses using AWS pay a subscription fee to enable reliable online communication between their companies and customers. Many companies prefer to use the AWS services and depend on them to operate, rather than building and maintaining those services internally, which is far more costly and, in many instances, less secure. AWS has demonstrated computing power to handle the massive amounts of traffic that has come to its site ever since it started operating in 2006.

According to an HG Insights' report published in 2025 [3], AWS has a market share of 30% of the global cloud infrastructure market with 4.19 million customers geographically situated in North and South America, Europe and Middle East and Asia-Pacific region – this easily explains the significant global impact upon AWS outage. The incident in the cloud provider infrastructure affected banks (HALIFAX bank, LLOYDS bank), airlines (Delta Air Lines, United Airlines), media, many websites and applications. A number of online services including Venmo, Snapchat, Fortnite, Facebook, Prime Video and Amazon's cloud computing were not functional. CNN reported that Coinbase, a cryptocurrency exchange as well as the artificial intelligence company Perplexity had technical disruptions. Many customers were not able to view/access their funds.

The main cause of the incident seemed to be an issue in the Domain Name System, an internet location engine, converting user-friendly web addresses into IP addresses (a series of

numbers that other websites and applications can understand). The company kept its customers informed about the recovery steps undertaken. However, the situation proved the need for better preparedness and showed the importance of addressing the concentrated risk. The main aim should be to minimize and if possible, avoid the enormous effect in view of the interconnectedness of the operators – in the AWS case, the impact was from consumer applications to financial and public sector services.

Another interesting example dates back in July 2024 [4], when a software glitch during an update made by the US-based cybersecurity company CrowdStrike wreaked havoc across sectors globally. Airlines were forced to cancel flights, hospital disruptions were observed and businesses were not able to access their internal platforms. The event showed the fragility of the global economy in view of ICT service and the vastly spread dependence on computer systems.

At that time, numerous companies used CrowdStrike's cybersecurity software to block cyber threats. Upon updating their cybersecurity software, computers running with Microsoft Windows crashed because of the faulty way a code update issued by CrowdStrike interacted with Windows. Although, the company had significant experience with more than a decade of being present at the market, this result led to blocking the functioning of many operators and later the declared costs were more than \$5 billion in direct losses. Currently, app 10 000 companies use CrowdStrike.

In this case, obviously, more diversity in the cyber security providers could minimise the impact. At that time however, the dominance of a number of companies in the anti-virus and threat-detection field created risks.

Meanwhile, initiatives to prevent market disturbances have already started at national and supranational levels. In 2016, directives were given to the EU member states to adopt national strategies on network and information systems [5]. This horizontal measure covered three types of financial entities – credit institutions, trading venues and central counterparts. The countries were able to identify operators of essential services but only for those three types of financial entities. The exact rule for this identification (called size-cap rule) is later established in the NIS 2 Directive [6].

Currently, there are approximately 22 000 financial entities operating in the European Union. Every incident occurred in one of those entities concerns also others interconnected and poses risks for the functioning of the businesses but also for the consumers. To address this and to facilitate the digital functioning in the financial sector, and consequently to enhance the operating of the single market, the legislators proposed preventive measures for stability.

The EU financial sector is regulated by the Single Rulebook and the governance is provided by the European System of Financial Supervision. Up till 2022, there have been legislative differences and separate approaches in tackling ICT risks by the national authorities. This could be a factor distorting the competition between the financial entities operating in different member states and consequently, could occur to the detriment of the market participants. In addition, there were gaps or overlaps in digital operational resilience testing, which is not cost effective and showed the need for more cooperation and alignment at least at European level both in preventing incidents but also in mitigating their impact once they have occurred. As a result, new legislation was proposed targeting the updating of the ICT risk requirements such that they are not covered only by capital requirements, as was the case in the past. The new legislation targeted also to establish equal rules for financial entities when assessing and addressing ICT risk.

This brought consistency and more confidence in the EU financial system. Additional costs were avoided by minimising the risk of ICT disruptions. Also, the legal certainty was increased, more simple rules were introduced and in cross-border cases, more convergence

was established - the legislators introduced the European Regulation 2022/2554 on digital operational resilience for the financial sector [7], which entered into force on 16 January 2023 (with the abbreviation DORA – Digital Operational Resilience Act).

3. Ensuring control

As mentioned, some financial entities were already part of the ecosystem of the NIS-2 Directive in 2022. The national competent authorities as well as the three European Supervisory Authorities (the European Banking Authority, the European Securities and Markets Authority and the European Insurance and Occupational Pensions Authority) participate in the workings of the Cooperation Group and the computer security incident response team CSIRTs, both established under the same Directive. This enabled the smooth exchange of information and lessons learned experience.

In order to address the need for more joint efforts to prevent the cyber-attacks and the related risks in the financial sphere at European level, DORA introduced new cybersecurity rules. Increased investment in security and regular risk testing is required to ensure the good functioning of the financial entities' businesses. DORA established a broad resilience framework in the financial sector for both financial entities and their ICT providers that are identified as critical.

Many financial institutions prefer to use providers for software solutions, cloud services, data processing. This has led to a risk of cyber threat to those providers, which may also compromise financial institutions themselves. With the introduction of DORA in the European Union, financial institutions must carry out thorough procedures to manage risks associated with external providers and carry out regular security tests. The European Banking Authority, the European Securities and Markets Authority and the European Insurance and Occupational Pensions Authority are the leading supervisors and ensure the monitoring of critical service providers in the EU on the risks they can pose to the financial sector. On-site and remote inspections are foreseen and recommendations are to be issued.

In 2023, the mentioned European Supervisory Authorities issued a report on the state of information and communication technology providers in the EU [8]. The document indicates that there are approximately 15000 service providers directly serving the EU financial sector. They support many critical or important functions of the financial entities. Separately, some of the providers consequently use sub-providers and thus the number of ICT providers reaches around 20 000. Of course, the risk of using these services depends on the level of criticality of the service and it is estimated that around 9 000 service providers serve activities for financial institutions identified as critical or important. Some of those services are development and deployment of software and applications, network infrastructure services (excluding telecommunication services), data centres (physical), ICT advice and managed ICT services, information security and cybersecurity services (including control and monitoring, intrusion testing, security operations centres, etc.), cloud computing and data analytics and other data related services. Most of the companies providing these services focus their work mainly on one area. Software and application development is the activity where most financial institutions use suppliers.

The critical ICT service providers were first identified by the ESAs in November 2025. The number of entities identified under the EU framework are currently 19 and they specialise in different services.

The financial entities themselves manage the ICT third-party risk while the member states competent authorities accomplish the financial supervision of ICT risks. The oversight function of the European Supervisory authorities complements the ICT risk supervision.

4. International practices

At the international stage, there are a number of frameworks for operational resilience established in the UK, the USA, Singapore, India, others. Globally, the G7 Cyber Expert group functions as a working group that meets annually to discuss the cybersecurity policies and strategies in the member countries of interest to the financial sector. The group was established in 2015 and the chairs are representatives of the Bank of England and the US Treasury. The countries (Canada, France, Germany, Italy, Japan, the UK and the USA) exchange information, cooperate and discuss incident responses during their four meetings per year. On annual basis, an incident response test is organised and every four years cross-border cyber exercises take place. The work is reported to the G7 Finance Ministers and Central Bank Governors. Non-enumerated members are the European Banking Authority, the European Central Bank and the European Commission.

One of the latest topic of discussion of the G7 Cyber Expert Group is AI and the risks it could pose to the financial system [9]. After the development of the ICT systems, AI is the next step of the expanding innovation that could further transform the financial system. It could be used by the financial entities and authorities to improve their operations, analyses and risk management. However, AI is explored also by malicious actors and particularly generative and agentic AI could lead to new cybersecurity risks. In this view, it seems inevitable for the authorities to establish partnerships with the academia and technology firms to counterfeit those threats.

In the constantly evolving environment nowadays, a number of cyber security and resilience frameworks were developed to become operational internationally. Some of them are listed below with the aim to generally present the cyber security measures globally.

NIST Cybersecurity Framework

The National Institute of Standards and Technology (NIST) within the US Department of Commerce has established the second version of its cybersecurity framework [10] and provides support for the entities to manage their cybersecurity risk. The system of cybersecurity outcomes is provided and no instructions are given how they have to be achieved, which is left for the managers of the risk. This framework is available further to multiyear cooperation between the industry, academia and the government of the USA and is considered to be one of the best frameworks. It has horizontal context and can be applied no matter the size and the sphere of work of the entities.



Figure 1. Illustration of NIST Cybersecurity Framework (Source: National Institute of Standards and Technology, US Department of Commerce)

The core components of the NIST Cybersecurity Framework are identify (understand the entities' environment), protect (ensure the delivery of critical services), detect (recognise cyber threats rapidly), respond (actions taken upon cybersecurity incident) and recover (restoring services weakened further to an incident).

The UK example

The UK as a member of the G7 Cyber Expert group has its own framework for improving the resilience of the financial sector. The country authorities highlight the importance of assessing the cyber risk by the individual companies and the financial markets infrastructures such that they are well prepared for and can adequately respond to cyber threats and incidents. The following tools are used for cyber assessment – CBEST, STAR-FS and CQUEST.

CBEST (Critical National Infrastructure Banking Supervision and Evaluation Testing) is a framework for regulating authorities in the UK to work with companies using a mock cyberattack on the people, processes and technology (in live production systems). The basis for the simulated attacks includes the current cyber threats trends with the aim to improve the company's resilience. In testing the firm's defenses, the regulators can assess their ability to detect and respond to cyber threats. The simulation itself is accomplished by accredited service providers and they act following legal, ethical and moral obstructions in view of the fact that the testing is accomplished on live production systems.

Every year, a CBEST thematic report is published to inform the private sector about the current cyber threats such that the entities could review and strengthen their ICT systems and tools. As regards 2025, the report is expected to include details in respect to the management of ICT and cyber risks. In the 2024 report [11], it is highlighted that there are still gaps in the foundational cyber defenses. The entities should introduce improvements as regards assessing the cybersecurity risk to assets and individuals, cyber risk management, detection of cyber threats and cyber incident response to mitigate impact. The firms still show weaknesses in their threat intelligence, namely on the integration of threat intelligence with business lines. In 2023, the need for a strong foundation of cyber hygiene is highlighted, i.e. practices for preventing cyber incidents like training and awareness raising campaigns, maintenance of assets and detection capability. CBEST help firms assess their resilience and review their capabilities against attackers looking to disrupt important business services.

STAR-FS (Simulated Targeted Attack and Response assessments for Financial Services) is a tool to assess the cyber resilience of the important services of firms. This way the firms and national authorities have better view of the vulnerabilities and can take remedial actions. Threat led penetration testing is encouraged, which mimics the action of cyber threat actors. Financial institutions interested in the STAR-FS assessment can establish contacts with their supervisory authority and gain more information about their technical capabilities to protect, detect and reply to cyberattacks (including systems, people and processes).

CQUEST (Cyber resilience questionnaire) is used to assess cyber risk and resilience capabilities mainly in the UK bank sector but also other firms. It contains a questionnaire with 50 questions covering 6 domains: Governance and Leadership, Identify, Protect, Detect, Respond and Recover. The supervisory authorities might provide guidance further to the information received from the questionnaire.

Cybersecurity framework in Singapore

Singapore's cybersecurity framework represents a centrally coordinated approach to protect the critical information infrastructure. The legal foundation is in their Cybersecurity Act, which was recently amended in 2024. The updated legal framework for oversight and maintenance of the national cybersecurity includes new categories of regulated entities. The

Cyber Security Agency can respond when threats materialise. Recognizing that cybersecurity is a shared responsibility, Singapore also established a structured framework for sharing information and thus strengthening awareness and improving coordinated responses. At the same time, a licensing framework for cybersecurity service providers has been implemented to raise professional standards. There is a strong emphasis on people to nurture a vibrant cybersecurity ecosystem and sustain a talent pipeline.

India

In India, the authorities recognise the importance of cyber risk in a high-risk category. They accomplish public consultations and organise impact analyses with the aim to periodically review the landscape and issue guidelines. In the banking sector, the authorities organise a specialised IT supervision as from 2015. They prepare cyber mapping exercise and request enforcement and corrective measures, if needed in review of 24 different security domains (such as network security, application security, database security). Incidents have to be reported to the reserve Bank of India within 2-6 hours. Security Operations centre are available non-stop. Dedicated agencies have been established to protect the digital infrastructure.

5. TIBER-EU framework and Thread-Led Penetration testing

In Europe, TIBER-EU framework (Threat Intelligence-Based Ethical Red Teaming) provides operational requirements and guidance on how to perform testing, to leverage the learning based on the test results and as a result to improve the cyber resilience of the financial entities in the EU member states. TIBER-EU tests mimic the tactics, techniques and procedures of real-live attackers. It is tailor made to simulate an attack on the critical functions of the entity as well as its people, procedures and technologies. The test will reveal the strengths and weaknesses of the financial entity and will provide information for updating its cybersecurity level.

Following similar initiatives in the UK (and the Netherlands also), the TIBER-EU framework was built jointly by the European Central Bank (ECB) and the national central banks in the EU. It was published in May 2018 and a new edition of the Guidance is available as of January 2025 [12].

The requirement to test the ICT environment of financial entities is established with DORA regulation and has to be performed annually. Some organisations are subject to an additional testing – Threat-Led Penetration Testing (TLPT), which is required for financial entities whose failure would have systemic impact.

The usual testing aims to strengthen the security level of the entities while the TLPT has to confirm that the security level of the entity is appropriate. For more information as regards both TIBER-EU and TLPT, please see Table 1.

Table 1. Indicators as regards TIBER-EU framework and DORA TLPT

Indicator	TIBER-EU	DORA TLPT
Legal basis	NIS 2 Directive	DORA
Date of publication	May 2018	Dec 2022
Adoption	Voluntary	Mandatory

Mandatory	Voluntary framework	Legally binding regulation
Countries of application	Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, the Netherlands, Norway, Portugal, Romania, Slovakia, Spain and Sweden.	EU member states
Mandatory elements	Four areas and two types of requirements are mandatory	Does not fully cover all the requirements of TIBER – EU framework. Compulsory for the financial entities across EU at frequency chosen by the TLPT authority (generally, 3 years).
Use of internal testers	Not envisaged	Possible under certain conditions
Purple teaming (joint testing of the red team (testers) and the blue team (staff from the attacked institution))	Not mandatory	Mandatory in the closure phase, similarly to the replay workshop
Sectors approach	Sector-agnostic approach	No sector specific or entity specific requirements
Selection of experience testers and intelligence providers	TIBER-EU procurement guidelines	Requirements in Art 27 of DORA and Regulatory Technical Standards specifying elements related to thread led penetration testing

In brief, the TLPT is a large scale exercise that simulates a real cyber attack on the financial entity. The TLPT includes physical and virtual testing. The physical test checks the possibility for on-site penetration and the virtual one is addressed to the ICT resources. The TLPT also ensures the coverage on the financial entities' employees – who can be a target of social engineering or blackmailing. Main principle during the testing is to achieve success by any means.

The main difficulties during TLPT are connected to:

- High operational risk since the test is accomplished on live production environment; there is a risk of service disruption or data lost or modification;
- ICT maturity requirements – in case the financial entity does not have a sufficient maturity, it should not go under a TLPT since they will not be resilient to handle the testing;
- Complexity of coordination – the tests involve different participants and coordination could be challenging while maintaining secrecy and compliance.

- Confidentiality and access controls – information must be shared only on a need-to-know basis; the governance could be complicated;
- Expertise - the TLPT require high skilled testers and threat intelligence providers. Searching for such experts can be difficult, time consuming and costly;
- The active red teaming phase usually takes place for 12 weeks and requires good planning and resource management;
- Risk management burden – the financial entities which undergo a TLPT takes full responsibility for risk management and continuous monitoring during the test.

The TLPT is to be accomplished in accordance with the TIBER-EU framework in force as of 8 July 2025. The criteria used for identifying financial entities that have to perform TLPT are specific and defined in a dedicated Regulatory Technical Standards as regards the requirements to use the internal testers, the requirements in relation to scope, testing methodology and approach for each phase of the testing, results, closure and remediation stages and the type of supervisory and other relevant cooperation needed for the implementation of TLPT and for the facilitation of mutual recognition.

The financial entities that have to undertake a TLPT are identified as per the principle of proportionality. Two-layers approach is applied and the following factors are assessed: impact (what will be the extend of impact in case of disruption of the services of the financial entity); financial stability (systemic impact at EU and national level) and ICT risk (level of ICT). The entities that are functional in core financial services and play a systemic role are subject to TLPT. It is possible that a TLPT authority decides to opt-out or opt-in a financial entity. Also, a TLPT authority may decide to perform a pooled or joint TLPT.

Pooled testing and joint testing

The pooled testing is accomplished when several financial entities will be in the scope of the TLPT, for which an ICT third party services provider will procure an external tester but only if it is expected that the non-pooled test have an adverse impact on the quality or security of services to customers that are entities falling outside of the scope of DORA or the confidentiality of the data related to such services. There are specific requirements for the pooled testing in connection to the remediation plan, the cooperation of the TLPT authorities and the attestation.

The joint testing involves several financial entities using the same ICT intra group service provider or belonging to the same group and using the same ICT systems.

The TIBER-EU framework includes four areas and two types of requirements including some optional requirements. The adoption of the framework is voluntary, if the respective country authority decides to adhere to the framework but once adopted the authority shall implement mandatory requirements.

It is possible to have cases of pan-European competent authorities. For trade repositories, credit rating agencies or critical benchmark providers, the European Securities and Markets Authority is the competent authority. The ECB is competent for credit institutions classified as significant (in accordance with Art. 6(4) of Regulation EU N1024/2013).

Participants

In TLPT, we have the following teams involved in the process:

- TLPT cyber team – includes the responsible people in the respective TLPT authority;

- Control team or called also white team – consists of the responsible people within the financial entity who manage the ongoing TLPT exercise. It deals with procurement, risk assessment, risk management;
- Blue team – consists of the responsible people protecting the financial entity against cyber threats; they do not have information about the testing;
- Threat intelligence provider – responsible for mimicking hacker information gathering;
- Internal and external testers – similar to the red team of TIBER-EU framework; DORA permits the use of both internal and external testers.

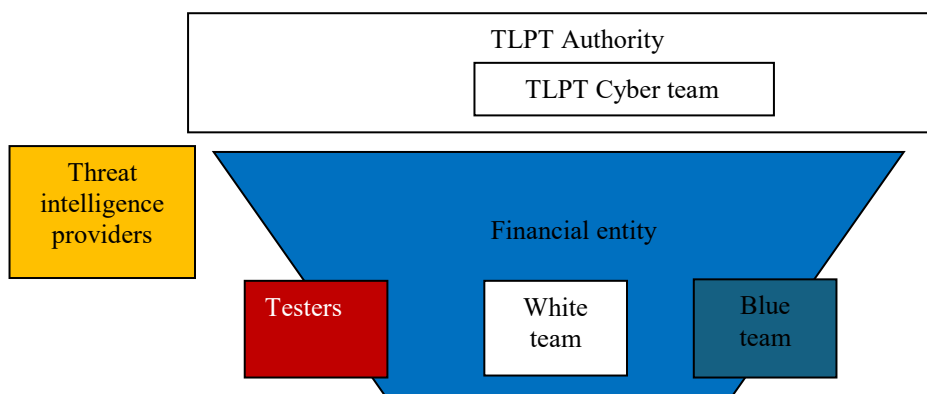


Figure 2. TLPT participants

Phases of TLPT

In general, every 3 years, threat lead penetration testing has to be accomplished for the critical ICT providers of services in the financial sphere. The responsibility lays within the financial entity – it accomplishes the test and bears all risks in relation to it. The process consists of three main phases – preparation, testing and closure.

During the **preparation phase** the control team is formed, the scoping formulation is identified and the testers are selected. In principle, this is the phase when good planning is to be accomplished. The TLPT authority should anticipate and inform financial entities about the forthcoming test and inform about the requirements. As next step the financial entities should start searching for suitable testers and threat intelligence providers as soon as possible after the notification and before the official start of the testing. Therefore, the preparation phase starts with the notification from the TLPT authority and includes procurement activities and risk management preparation. The phase is characterized with the drafting of the initiation documents (3 months) and documents to specify the scope of the testing (6 months).

In the **testing phase**, we have the threat intelligence part with scenarios which have to be tested during the red teaming part and the active red teaming test has to be at least 12 weeks.

The **closure phase**, which is similar to the one in the TIBER-EU framework, starts with the revealing of the TLPT to the blue team. The blue team and the red team replay some defensive and offensive actions carried out during the TLPT and a purple team exercise also takes place. The financial entity drafts a test summary report and a remediation plan and sends them to the TLPT authority. The process closes with an attestation from the TLPT authority.

Currently, it seems that there is a limited number of testers and threat intelligence providers in the market. Therefore, the requirements for the testers are not rigorous. In addition, there is a possibility that the providers do not cover the requirements but only in cases

when the financial entities mitigate any additional risk this introduce. Nevertheless, the threat-led penetration testing has established a good ground for better digital functional of the financial system in the EU.

6. Conclusion

In conclusion, the dynamic evolution of the financial sector towards digitalisation has led to new cybersecurity risk management practices and the adoption of new frameworks for cybersecurity and threat-led penetration testing. In this way, not only the regulators reinforce operational resilience but also foster greater alignment and collaboration across borders. As cyber threats continue to grow in sophistication and frequency, the financial sector must remain constantly ready, investing in regular testing, skilled personnel and adaptive frameworks. Eventually, the ongoing commitment to strengthening cybersecurity will underpin financial stability, ensuring that the interconnected global financial ecosystem can withstand and recover from disruptive incidents while maintaining trust and confidence among stakeholders.

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Countering Generational Disenfranchisement: Bipartisan Strategies to Enhance Homeownership for Millennials and Generation Z

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Abstract. The paper reviews current trends in US youth home ownership and links the declining rates across the Millennials and Gen Z population to potential disenfranchisement and radicalization as evidenced by existing empirical research and theory. As American democracy finds itself in a precarious position characterized by political violence, hate speech and policy polarization, the authors suggest that building an across the isle political consensus for improving home ownership among the youngest generations can be used as a tool for moderation and normalization. A brief review of a cross-ideological imperative on the topic proves that there is a realistic and achievable political consensus to be reached on policies that sustainably improve home affordability without imposing significant political costs on either major party even in the current political and media climate.

Keywords. Home ownership, American democracy, millennials, genz, radicalization, liberalism, conservatism, Judeo-Christian values.

1. Introduction

Home ownership is the essence of the American dream, symbolizing stability, predictable wealth accumulation, an anchor for civic engagement and local community integration, a safe space to raise a family and ultimately a valuable asset to pass down to the future generations, serving as a minimum guarantee that they will enjoy a better life and pursue higher opportunities than their parents.

However, recent trends indicate a sharp decline in homeownership rates among Millennials (born 1981–1996) and Generation Z (born 1997–2012), compared to the Silent Generation, Baby Boomers and Generation X at similar ages (Gregory, 2023; Gregory & Bloodworth, 2023). This shift is driven by factors such as wage stagnation, rising housing costs, student debt, and delayed life milestones like marriage and children (Isom, 2024; Gregory & Bloodworth, 2023).

While these barriers exacerbate economic insecurity, their broader implications extend to the sustainability of democracy and capitalism. Declining homeownership intensifies wealth inequality, fosters social re-stratification, and breeds resentment toward market systems, potentially leading to democratic apathy, radicalization, and a shift toward socialist ideologies (Forrest & Hirayama, 2018; Franc & Pavlović, 2018; Faria, 2022).

This paper argues that without intervention, these trends could undermine the mutual reinforcement of property ownership, democratic participation, and capitalist prosperity, as envisioned in the concept of a "property-owning democracy" (Vitali, 2023).

2. The threat of declining home ownership among millennials and generation z to democracy and capitalism in the United States

In her study, Gregory (2023) finds significant gaps in both median income and home ownership between the Silent Generation, Baby Boomers and Generation X on one hand and the Millennials and Generation Z, on the other. According to her, at the age of 30, “the median non-college-educated Millennial made 23% less than the median Silent Gen’er, 12% less than the median Boomer, and 4% less than the median Gen Xer” (Gregory, 2023). This gap in median income is an underlying foundation for a similar gap in home ownership, which however is exacerbated by the general inflationary processes for homes in the recent decades. The gap in some of the cohorts is especially striking and provides an obvious factual underpinning for the anecdotal evidence of intergenerational tensions today. For instance, at age 30, “non-college-educated Boomers were about twice as likely as non-college-educated Millennials to own homes: 49% vs. 24%, respectively” (Gregory, 2023) (Figure1.):

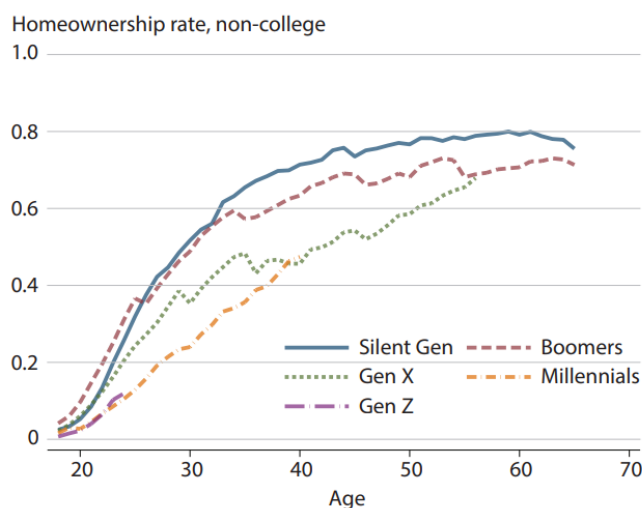


Figure 1.

The income gap among college educated cohorts closes sharply with Millennials at the age of 35 actually earning more than their Gen X and Boomer counterparts (Gregory, 2023). This phenomenon can be explained to some extent by the rising returns of college education across generations as argued by Autor (2024), though the financialization of the economy and the shift towards services-based entrepreneurship based on the coastal rural agglomerations may also be playing a part.

Yet, the home ownership gap in the college educated cohorts is also present as “at age 30, 38% of college-educated Millennials owned homes, less than the 54% of Boomer college-educated workers and even the 49% of Boomer non-college-educated workers of the same age” (Gregory, 2023) (Figure 2.):

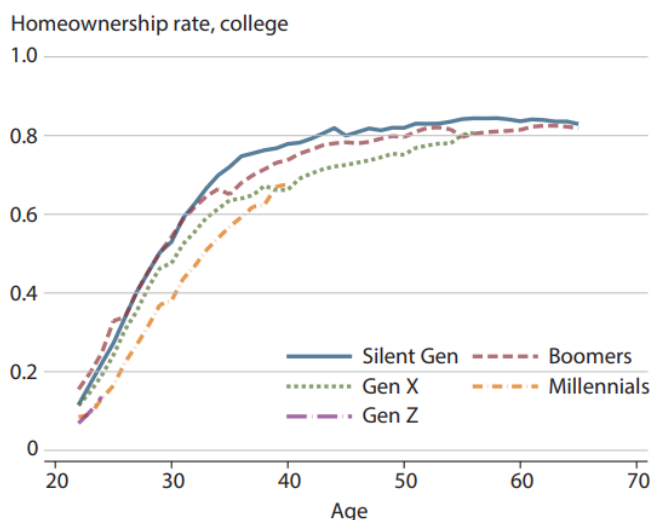


Figure 2.

Gregory (2023) argues that the persistence of the home ownership gap across generational groups who do not display an income gap point to “differing incomes and labor market opportunities are only part of the story”. Inflationary pressures and wealth inequality are almost certainly putting negative pressure on the home ownership of younger generations today. A steeper entry level to the home market results in nearly half of young people between 18 and 29 now living with their parents – the highest share since the Great Depression (Isom, 2024) and almost doubling the same number during the post-WW2 economic boom. Isom (2024) also points to the prevalent lifestyle decision to delay marriage today as another barrier to owning a home by successfully paying down a mortgage as the AI Housing Center has found out that having a second borrower (most often a spouse) is significantly reducing the risk of default.

As already pointed out, the general financialization and pro-inflationary shift of the US economy has also had a profound impact on housing affordability and worker compensation. The Economic Policy Institute (2021) has calculated that the average annual growth in productivity and compensation for the period of 1948 – 1979 has been 2.5% and 2.1% respectively with the two diverging afterwards and the respective number being 1.4% and 0.6% for 1979 – 2025 (Figure 3):

Stagnating compensation levels have led to the median age of a first-time home buyer increasing to 38 years while the typical repeat buyer increasing further to 61 years with the median age of all buyers peaking at 56 years old (NAR, 2024). The numbers have increased remarkably throughout the last decades – for instance, in 1981, the median age of a first-time buyer was 29, the median age of a repeat buyer was 36 and the median age of all buyers was 31 (NAR, 2024).

This disparity is bound to create tensions between generations which have recently started to emerge from anecdotal evidence (Gaviola, 2019) to empirically established observations (Pisano, 2025; Bass, 2025) backed by statistical data that establishes that the biggest beneficiaries of the substantial run-up in home prices have been pre-late 1990s buyers (Macdonald, 2015).

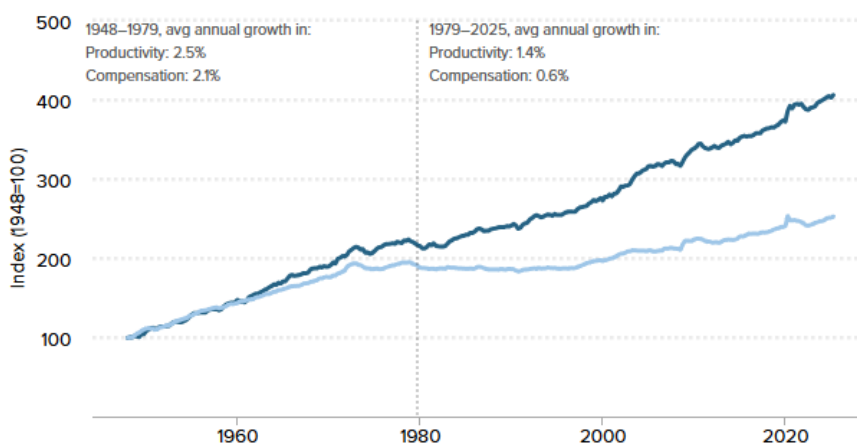


Figure 3.

A nationally representative poll conducted by Clever Offers, found out that American generations have started pointing the finger at each other regarding who is to blame for the housing affordability crisis that has taken over the country (Pisano, 2025) (Figure3.):

Although all generations seem to recognize the problems in the housing market, who's responsible is a more open question. Around a third of all respondents (31%) blame millennials most for the current affordable housing crisis, just ahead of boomers (27%). Notably, 35% of millennials selected boomers, while only 25% of boomers picked themselves. Meanwhile, 33% of boomers blamed millennials, while only 21% of millennials pointed the finger at their own generation. Somewhat surprisingly, respondents also see millennials (30%) as most responsible for the lack of housing inventory, as opposed to boomers (24%), who largely led the policy, planning, and business decisions that shaped the current market over the previous decades. Again, just 19% of millennials see themselves as most responsible for lack of housing inventory, while 30% of boomers feel this way. Meanwhile, only 24% of boomers chose their own generation, compared to 32% of millennials who selected boomers.

The same poll also found out a startling cleavage between the general perceptions of boomers and genz as home owners. The boomers are almost universally perceived as being most financial responsible (66%), most likely to oppose affordable housing (42%), least likely to buy a home as a status symbol (18%) but also the most likely to report neighbors to the HOA while not following neighborhood policies themselves (37%) (Pisano, 2025). On the other hand, genz are perceived by far as the least financially responsible (57%), the most unrealistic about what they deserve in a home (57%), most likely to overpay for a home out of desperation (40%), most entitled when it comes to home ownership expectations (31%) but also the biggest victim of the current housing crisis (45) (Pisano, 2025).

Higher interest rates and longer mortgage terms will exacerbate the perceived plight by millennials and generation z as they will be the first generations to face higher total projected mortgage repayments during the second half of the mortgage (Hamptons, 2024). This will squeeze this generation at a time when they are starting families or pursuing significant advancements in career and income, expecting these to translate into pleasure or substantial savings and investments. Researchers from the Grattan Institute in Australia have found out that millennials will also have higher expected total mortgage repayments as a share of expected total income during the loan, almost doubling the number for baby boomers (Khadem, 2023; Moloney and Coates, 2022; Coates, Moloney and Clay, 2022).

Finally, it is important to note that the general affordability crisis may create distorted perceptions among the young generations who are at the early stages of acquiring homes and repaying the mortgage as a simply temporal factor. While the general affordability hurts voters of all ages, the fact that it takes place at a time when millennials are still struggling with the first years of repaying the mortgage and the generation z are entering the labor force boosts their subjective vulnerability to the problem. The National association of home builders (2025) publish an annual “graph” of home affordability that indicates the scale of the affordability problem’s impact as nearly 60% of US households (76.4 million out of a total of 134.3 million households) are unable to afford a \$300 000 home with the median-priced new home in 2025 being priced at \$459 826:

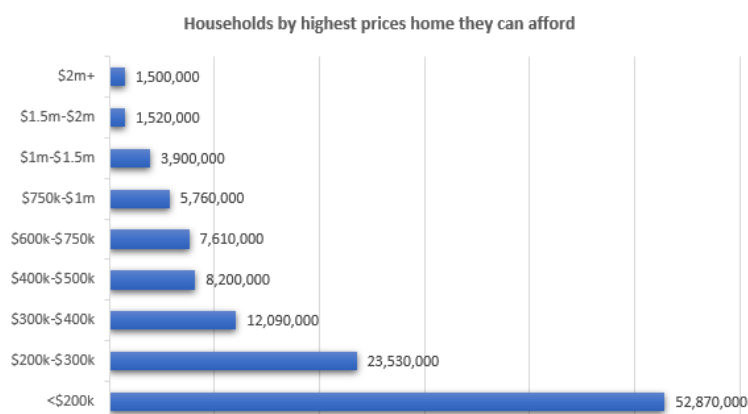


Figure 4.

The National association of home builder’s (2025) assumption is actually underestimating the burden that the millennials and generation z are taking to finance home ownership as it is based on conventional underwriting standards that assume the cost of a mortgage, property taxes and property insurance not exceeding 28% of household income (both generations are observed to taking more than 30%). In other words, the minimum income needed to finance a purchase of a \$200 000 home with a mortgage rate of 6.5% is \$61 487, meaning that at the base of the graph there are 52.87 million American households unable to afford even this home.

3. The foundations of home ownership in America’s Democratic and Capitalist system – from Greek philosophy to Judeo-Christian values

Philosophers such as Aristotle, John Locke, and Alexis de Tocqueville laid intellectual groundwork emphasizing property’s role in balanced governance, while American founders like Thomas Jefferson and James Madison adapted these ideas to envision a republic of independent proprietors. Aristotle, in *Politics*, argued that moderate property ownership by a robust middle class was essential for political stability, preventing the extremes of oligarchy and mob rule. He posited that "the most perfect political community must be amongst those in the middle rank," as they "neither covet... nor are coveted by others," fostering a balanced polity where virtue prevails over factionalism (Aristotle, trans. 2009). For Aristotle, excessive wealth bred arrogance, while poverty incited sedition; thus, "it is best to have property private,

but to make the use of it common," ensuring subsistence without communal inefficiencies (Aristotle, trans. 2009). This middle-class emphasis stabilized governance by mediating class conflicts, a principle echoed in America's capitalist ethos where homeownership democratizes wealth accumulation.

John Locke extended this in Second Treatise of Government, viewing property rights as natural and pre-political, derived from labor: "every man has a property in his own person: this no body has any right to but himself. The labour of his body... are properly his" (Locke, 1689). Property encompassed "lives, liberties and estates," essential for liberty against arbitrary power (Locke, 1689). Government existed to protect these, as "the great and chief end... of men's uniting into commonwealths... is the preservation of their property" (Locke, 1689). Locke's labor theory justified capitalist acquisition while limiting it to prevent spoilage, aligning with democratic consent: Taxes required majority approval, safeguarding individual estates (Locke, 1689). This framework influenced America's Bill of Rights, embedding property as a bulwark against tyranny.

Alexis de Tocqueville, observing 1830s America, praised equality of conditions—facilitated by partible inheritance—as stabilizing democracy. In *Democracy in America*, he noted that "land is the basis of an aristocracy," but egalitarian division created smallholders, reducing class strife: "No sooner was the law of primogeniture abolished than fortunes began to diminish" (de Tocqueville, 1835). This fostered civic engagement, as "everyone has property of his own to defend" (de Tocqueville, 1835). Yet, he warned of risks: Excessive equality could breed individualism, but property ownership countered this by tying citizens to community interests, ensuring democratic vitality (de Tocqueville, 1835).

These ideas informed American founders. Thomas Jefferson idealized yeoman farmers as "the most valuable citizens," embodying republican virtue through self-sufficiency: "Cultivators of the earth are the most valuable citizens" (Jefferson, as cited in Phillips, 2018). Property ownership ensured independence, vital for democracy: "The small land holders are the most precious part of a state" (Jefferson, as cited in American Heritage, n.d.). James Madison, in *Federalist No. 10*, linked property to republicanism: "From the protection of different and unequal faculties of acquiring property... results" factional diversity, managed through extended republics (Madison, 1787). Government protected "property of every sort," including rights, to sustain liberty (Madison, 1792).

Jeffers and Adams drew their vision on integrating property into the republic's framework from Judeo-Christian tradition. Encompassing the Hebrew Bible (Tanakh/Torah for Judaism) and the Christian Bible (Old and New Testaments), it has profoundly influenced American political thought, embedding property ownership with moral, stewardship, and communal dimensions.

In Judaism, the Torah (first five books of the Hebrew Bible) frames property ownership as a sacred trust from God, emphasizing inheritance, justice, and limitations on alienation. This philosophy underscores homeownership's importance in fostering communal stability, a precursor to democratic equity. Central is the concept of *nachalah* (inheritance), where land is apportioned as a perpetual family holding, reflecting God's covenant with Israel. For instance, in Numbers 26-27 and 36, the Torah addresses inheritance rights, notably for Zelophehad's daughters, mandating: "The inheritance of the people of Israel shall not be transferred from one tribe to another, for every one of the people of Israel shall hold on to the inheritance of the tribe of his fathers" (Numbers 36:7, ESV). This ensures equitable distribution, preventing concentration of wealth and mirroring capitalist ideals of opportunity while curbing excesses through divine oversight.

Leviticus 25:23 explicitly limits absolute ownership: "The land shall not be sold in perpetuity, for the land is mine. For you are strangers and sojourners with me" (ESV). Here,

humans are stewards (*gerim v'toshavim*), not owners, aligning with sabbatical and Jubilee years where debts are forgiven and lands revert (Leviticus 25:10-13). This cyclical restoration combats inequality, philosophically underpinning democratic safeguards against oligarchy. Deuteronomy reinforces this with inheritance laws: "If a man has two wives... he may not treat the son of the loved as the firstborn in preference to the son of the unloved... but he shall acknowledge the firstborn... by giving him a double portion of all that he has" (Deuteronomy 21:15-17, ESV). Such provisions promote familial stability, essential for capitalist productivity, as secure homes enable labor and innovation.

These Torah principles influenced American democracy by inspiring land reforms. Jefferson, drawing on biblical agrarianism, advocated for smallholdings to cultivate republican virtue, echoing Torah's anti-monopolistic ethos (Novak, 2002). In capitalism, this stewardship tempers profit with ethics, as seen in Jewish legal traditions prohibiting boundary removal: "You shall not move your neighbor's landmark" (Deuteronomy 19:14, ESV). This moral boundary protects property rights while fostering communal harmony, vital for democratic pluralism amid market competition (Forrest & Hirayama, 2018).

Christianity builds on Torah foundations, incorporating New Testament teachings that spiritualize property, emphasizing charity and eternal inheritance while affirming earthly ownership's role in societal order. This dual focus shaped America's capitalist democracy by integrating moral imperatives into economic freedom. Proverbs, shared with Judaism, highlights inheritance: "House and wealth are inherited from fathers, but a prudent wife is from the Lord" (Proverbs 19:14, ESV). This underscores homes as generational blessings, promoting stability that undergirds democratic participation—owners, rooted in communities, engage civically. The New Testament reframes property through Christ's teachings, viewing it as a tool for stewardship rather than hoarding. In the Parable of the Talents (Matthew 25:14-30), servants are entrusted with property to multiply, rewarded for faithful management: "Well done, good and faithful servant. You have been faithful over a little; I will set you over much" (Matthew 25:21, ESV). This endorses capitalist enterprise—investment and growth—while demanding ethical use, aligning with American ideals of opportunity tempered by responsibility. Acts 4:32-35 depicts early Christians sharing property voluntarily: "No one said that any of the things that belonged to him was his own, but they had everything in common" (Acts 4:32, ESV). Yet, this communality presupposes private ownership, as seen when Ananias sells land but lies about proceeds (Acts 5:1-4), affirming individual rights: "While it remained unsold, did it not remain your own?" (Acts 5:4, ESV).

4. Addressing the home ownership problems: a cross-ideological imperative for sustaining democracy and capitalism

Forrest and Hirayama (2018) observe similar patterns in home ownership across highly financialized economies – the United States, UK and Japan. They start off by pointing to the growth of individual home ownership in the post-war mature capitalist economies, which occurred within a society characterized by “the atomized, nuclear family; suburbanization; high growth; the conventional mortgage market and a young, working population”. They then argue that these conditions have changed and now they contrast between ‘real estate families’ or ‘accumulating families’ which maintain or further accumulate valuable multiple property assets over generations; ‘dissipating families’ which are forced to deploy and diminish their property assets accumulated in the exceptional era; and propertyless ‘perpetual renter families’ (Forrest and Hirayama, 2018). According to them, this leads to a social re-stratification driven by ownership of residential property and changing demographics which has a profound impact on social stability. The ensuing inequality with top quintiles owning about 80% of housing

wealth while bottom quintiles renting precariously (Burchard, 2025) may result in undermining the “property-owning democracy”, where diffuse ownership stabilizes society by fostering stakeholding; instead, concentrated housing wealth may start eroding social cohesion (Vitali, 2023). Franc and Pavlović (2018) link such inequality to radicalization, finding that perceived economic disparities correlate with extremist attitudes. In the US context, this polarization has led to millennials and gen z feelings of a rigged system spilling over into envy and resentment of successful people (Elson and King, 2025). In a poll conducted by Elson and King (2025), millennials and gen z exhibit higher than average envy, relatively disagreeing with showing sympathy to very successful people failing, relatively taking joy in seeing very successful people failing and relatively disagreeing with the statement that people at the top usually deserve their high position. The processes of re-stratification and polarization may perpetuate a deeply rooted environment of resentment and envy which undermines a merit-based capitalist system functioning under a democratic political order. Koopmans (2014) extends this to religious fundamentalism, where economic exclusion heightens out-group hostility, potentially radicalizing disenfranchised youth into terrorist actions. Koopmans (2014) is possibly the only study to have tested and confirmed a multivariable relationship between home ownership and religious fundamentalism as well as out-group hostility, establishing that people who live in rented housing are significantly more likely to express and be influenced by these.

As millennials perceive the system to be rigged by older generations against them and start pointing fingers, they are at risk of becoming disenfranchised which in turn threatens participatory governance. Some academicians such as Chaput (2020) documents and labels the process as “millennial democratic fatigue”, pointing to a lagging voter turnout among millennials. Chaput (2020) argues that although millennial voter participation increases with time, by 2016 they had still been unable to break 50%, something that the boomers reached in their third election cycle and generation X achieved in the sixth election cycle. Millennials also show a rapidly declining trust in government and both the major political parties, which also translates in almost half of this generation’s active voters registering as independents, significantly higher than the 39% of generation X and 37% of boomers (Chaput, 2020). Similarly, declining homeownership undermines capitalism’s legitimacy, shifting views toward socialism. Faria (2022) argues Millennials’ 51% favorable view of socialism stems from inequality perceptions, viewing capitalism as “rigged”.

Addressing the home ownership problems can be a cross ideological imperative that builds consensus across the political spectrum as it spans over a wide nexus of issues and solutions that can be prioritized accordingly – income and wealth inequality, property rights and increasing supply through deregulation and/or state support, tax incentives and public-private partnerships, boosting youth engagement and participation, even promoting environmental sustainability. Beyond the binary of Democrats and Republicans, U.S. politics comprises diverse voter coalitions: progressives and democratic socialists on the left; centrists and moderates bridging the center; fiscal and social conservatives on the right; libertarians advocating minimal government; populists on both flanks emphasizing anti-elitism; and environmentalists or Greens prioritizing sustainability. Each group has stakes in resolving homeownership barriers, as failure to do so risks eroding their core constituencies and ideological legitimacy.

For progressives and democratic socialists—core to the Democratic Party’s left wing, including supporters of figures like Bernie Sanders and Alexandria Ocasio-Cortez—addressing homeownership is vital to combating what is perceived as systemic inequality. These groups view housing as a human right and oppose it being transformed into a mere commodity or asset investment type. They see declining ownership as a manifestation of

neoliberal failures that widen racial, gender and class divides (Isom, 2024). Importance lies in their commitment to social justice: progressive Millennials and Gen Z face barriers like student debt and wage stagnation, perpetuating cycles of poverty and radicalizing youth toward extreme anti-capitalist views (Franc & Pavlović, 2018; Faria, 2022). While this group often praises aspects of socialism and even communism, the political leaders realize that they cannot let a substantial demographic group slip into genuinely opposing the capitalist future of the USA as this will open a path for conservatives to further brand liberals as too radical and tighten their grip on the moderates. By prioritizing policies that effectively assist young generation in attaining home ownership, progressives can retain young voters, who prioritize wealth-building through homeownership. Such policies may include progressive taxation on high-value properties, zoning deregulation and limiting the ability of corporations to acquire large number of homes as investment assets that could be popular across the isles with very few exceptions (for instance, radical libertarians).

Centrists and moderates, spanning establishment Democrats and Republicans (e.g., Biden-Harris supporters and Never-Trump conservatives), emphasize pragmatic, evidence-based policies to foster economic mobility. For them, homeownership's decline threatens the middle-class consensus that sustains bipartisan governance, as it erodes consumer spending and local tax bases. Importance stems from their focus on stability: Gen Z's delayed ownership correlates with lower workforce participation and innovation, hindering growth. Feasibility lies in cross-party reforms. Bipartisan efforts, like the Senate's housing supply bills, propose tax credits for affordable construction and streamlined permitting.

Fiscal and social conservatives, underpinning the Republican Party (e.g., evangelical voters and small-government advocates), see homeownership as central to family stability and self-reliance. The crisis is important because it undermines traditional values: Delayed marriage and children among Gen Z correlate with lower ownership, threatening demographic renewal and moral fabric. Conservatives view this as a failure of overregulation, alienating working-class voters who feel squeezed by inflation. Solutions fit conservative principles through deregulation and incentives; reducing zoning restrictions to boost supply is a key proposal; tax reforms, like expanding mortgage interest deductions for families, promote ownership without subsidies. Social conservatives could support community-based initiatives, such as faith-group housing co-ops, aligning with pro-family policies, which in turn may found support from both moderates and progressives.

Libertarians, often aligning themselves with Republican party fringes, would favor minimizing government intervention in the housing sector in order to boost housing supply and thus push prices down. The current housing affordability crisis is viewed by them as a product of government overreach, which could be fueled by good intentions, but has ultimately stifled the ability of entrepreneurs to provide sufficient supply for the increasing demand. Furthermore, libertarians would be concerned to grow young voter cohorts being radicalized against property rights and capitalism as they cannot root their careers and personal development in home ownership. The libertarian camp is likely to prefer the abolition of zoning laws in order to allow vertical development and market-driven supply, as well as radical state-level deregulation. Libertarians may reach across the isle finding support for increasing land and estate taxes in order to shift the tax burden away from income as they often deem personal income taxes to be unconstitutional, highly ineffective and unjust.

Populists in the camps of both Sanders and Trump would view the home ownership inequality and home affordability crisis as elite-driven unjust policies that disenfranchise youth and less affluent voters. Housing can be politically exploited by populists who thrive on division of “us” (workers, youth, less affluent people) versus “them” (affluent elites, multinational investors in American real estate, corporations thriving on cheap money

inaccessible for the masses). Addressing this can be a unifying issue that provides high political benefits to populists on both sides of the aisle who seek to tone down political rhetoric and steer away from radicalization that has recently spurred bursts of political violence - for instance, Cenk Uygur's relationship with Charlie Kirk and Bill Maher's dinner with President Trump. While these camps may disagree on solutions such as curbing immigration and rent control, they may coalesce on a cross-ideological push for limiting corporations in investing in residential real estate, higher taxes on high value estate, zoning reform and construction deregulation in order to increase supply.

5. Conclusion

Cross-ideological political solutions are essential to preserving youth trust in the American system of democracy and liberal capitalism. Disenfranchised and radicalized cohorts of generation z and millennial voters who suffer from the housing affordability crisis are a threat to all major political camps in the US two party system. At the same time, the problem itself and many possible solutions touch on topics that are wildly popular across the political spectrum – equity, markets, family, liberty, anti-elitism. In times of heated rhetoric, perpetual partisan bickering and aggressive deployment of institutions against the political opponent, cool-headed politicians and pundits seek to reach across the aisle in order to steer the US further from the outbursts of political violence and back to an effective debate and governance. Boosting home ownership for the younger generations may be a prime opportunity of enormous political benefits and very little costs.

As a final note, the US home affordability problems are not the direst among the developed economies with changes in real home prices and disposable income diverging much more drastically over the last half a century in Australia, the UK, Ireland, and Canada, for example.

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Artificial Intelligence in Managing Forced Migration: Evidence from Europe

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Abstract. Migration has emerged as a key challenge for European Union (EU) member states, particularly in light of the growing number of national and regional military conflicts, political persecutions, and persistent security shortcomings. This paper investigates the potential implications of artificial intelligence (AI) in managing forced migration within the EU. Employing a quantitative, data-driven research, the study analyzes basic characteristics of forced migration to the EU over the past decade and identifies best practices from MS that have effectively integrated AI-based tools into their migration management systems. In this regard, demographic data on asylum seekers arriving in the EU between 2015 and 2024 are extracted from Eurostat, while literature review and official public institutional data are utilized to examine the current applications of AI in migration management. The central research question explores whether AI can serve as a reliable and effective instrument for managing increasingly complex and mixed migration flows.

Keywords. Artificial Intelligence, Forced Migration, Asylum Seekers, Europe.

1. Introduction

Lately, the world has faced a growing number of conflicts, leading to significant global instability [1]. Regardless of their intensity, these instabilities frequently force people to flee their countries of origin in a search of a safer and better living conditions. The EU, due to its relatively supportive social and economic conditions and its established legal framework and asylum seekers' system, has become a primary destination for many migrants over the past decade.

A huge increase of asylum applications in the EU has been observed in the period 2014-2016 [2], which was mainly motivated by the civil war in Syria, part of the broader early 2010s Arab Spring protests, that emerged from widespread discontent with the Syrian government. Initially peaceful demonstrations against the President Bashar al-Assad escalated into violent repressions, and brutal armed rebellion, that lasted almost 14 years with the fall of the Assad regime [3]. This period marked what became widely referred to as the European migration crisis.

However, after a relative decline in asylum inflows between 2017 and 2021, immigration to the EU have again increased substantially, primarily triggered by the Russian invasion of Ukraine in February 2022 [4], as well as by other geopolitical and regional instabilities, such as the Taliban's takeover in Afghanistan [5] and periodically escalating tensions between Israel and Palestine, especially in the aftermath of the October 2023 Hamas attack [6]. These overlapping crises continue to challenge the EU's capacity to respond relevantly to ongoing humanitarian needs and migration pressures.

This paper has two primary objectives. First, it aims to examine the forced immigration trends to the EU over the past decade (2015–2024) through the extraction and analysis of

official data from Eurostat and Statista. Second, it seeks to evaluate the implications of current AI instruments in managing complex mixed migration flows. This evaluation will be conducted by gathering information from official sources such as the European Border and Coast Guard Agency (Frontex) and the European Parliament, as well as through a comprehensive review of relevant academic literature. The main research question put in this study is whether AI-based approaches can serve as reliable tool for managing forced migration inflows. By examining the potential applications of AI-based decisions in complex issues such as migration, this study aims to contribute to a broader understanding of the advantages of adopting such technologies, particularly in less developed EU member states.

2. Literature Review

Over the past few years, a rapid development and a growing use AI technology has significantly transformed many sectors, including healthcare, finance, education, and public governance, just to name a few. As AI instruments become widely integrated into decision-making processes, their application has expanded beyond coping commercial needs to areas, such as migration management.

This widespread use of AI has attracted the attention of scholars worldwide, as many recent studies examine the integration of AI-based tools into forced migration management, raising questions about both its potentials and its risks. The escalating interest towards this issue is presented in Rönsch's research, which offers a systematic literature review of AI applications in EU migration governance, highlighting the benefits of efficiency, however, expressing warnings about unregulated deployments that may compromise migrant rights [7]. On the other hand, Nalbandian proves that sophisticated AI tools have been used to register and manage vulnerable populations such as migrants and asylum seekers, however, without paying attention to "potential misuses of the data collected and the overall ethical and legal underpinnings of these operations" [8].

Legal and ethical concerns are expressed by Yang, Zuiderveen Borgesius, Beckers, and Brouwer who identify major risks associated with AI at EU borders, including threats to privacy, fairness, and legal recourse [9]. On the other hand, another study investigates the advantages of: firstly, predictive AI, aimed at the governments support in time estimation, destination and size of refugee inflows, and, secondly, the Natural Language Processing (NLP) integration within a broader repertoire of techniques to automate immigration systems. However, the paper suggests that to better harness the analytical power of AI, these tools should be recognized as "inherently political, in the sense that they enshrine a specific view of power and relations of subordination" [10]. Regulatory critiques, such as those emerging around the EU AI Act, argue that exemptions for migration-related applications undermine accountability [11].

Case-specific studies also raise critical points. For example, Molnar discusses how specialized accountability frameworks are essential to protect migrants' fundamental rights, including freedom from discrimination, privacy protections, and procedural justice guarantees such as access to impartial decision-makers and the right to appeal [12].

Across this literature, a consensus emerges: AI tools may support migration governance, but only when grounded in robust legal, ethical, and participatory frameworks.

3. Current Asylum Situation Analysis

As previously highlighted in the very introduction of the current paper, the contemporary world is confronted with a significant rate of crises and security challenges. The pushing factors that make people flee their countries of origin have different nature - they vary

from climate change, political instability, social inequalities, to poor economic conditions. In addition to these underlying causes, armed conflicts and other forms of violent unrest, persecution, etc. remain significant catalysts for forced displacement. To contextualize this phenomenon, Figure 1 presents data on ongoing conflicts worldwide, categorized according to their varying levels of intensity.

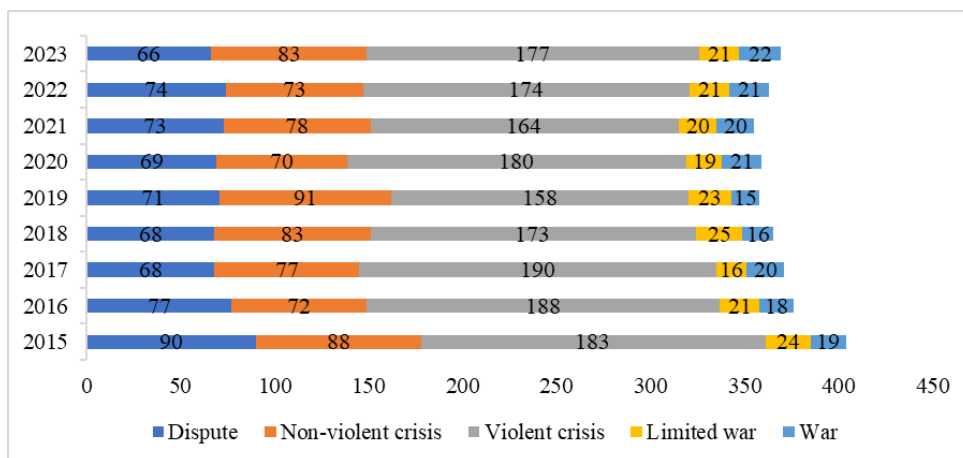


Figure 1. Number of conflicts worldwide from 2015 to 2023, by conflict intensity (Source: Statista [1])

As illustrated in Figure 1, the period under study reveals that more than 350 conflicts of varying intensity occur all over the world on an annual basis. These conflicts, at the roots of which stand variety of political, cultural, ethnic, territorial, and ideological contradictions lead to forced displacement of people. Europe, due to its better living standards and regulated immigration policies, is attractive destination.

In addition to the data in Figure 1, it should be noted that two peaks in conflict occurrence can be observed: the first in 2015, connected with the onset of the so-called European migration crisis for which it was already mentioned, and the second during the 2022–2023 period, marked by renewed and/ or newly triggered conflicts, such as the Russian invasion of Ukraine and some tensions in the Middle East and North Africa (MENA) region like between Israel and Palestine. These surges in the number of conflicts worldwide, as well as their intensity, correlate with the inflows of asylum seekers in the EU. The latest is further supported and confirmed by the data in Figure 2, which represents the number of first-time asylum applications submitted at the EU level on an annual basis between 2015 and 2024. Moreover, the comparison between two indicators demonstrates a direct relationship between rising global instability and the demand for international protection within the EU.

As visible from the data in Figures 1 and Figure 2 there is a relation between the number of ongoing conflicts between 2015 and 2024 and the volume of asylum applications, submitted within the EU in the same period. In other words, increased global violence tend to reflect in higher numbers of people seeking international protection in Europe. This trend, however, put the EU in a position, which requires the decision-makers and responsible public institutions to balance between fundamental human rights protection, on the one hand, and to keep the EU borders safe, preventing irregular immigration, on the other. Ensuring border security is a key priority, as some immigrants may pose security risks, including potential radicalization, terrorism, or extremism, however, it is not the only element of migration management system.

Once they have arrived and settled in the territory of the member states, the institutions in charge face other, no less important challenges such as social, economic and cultural integration. In this regard, some of the main advantages and disadvantages of applying AI-based methods in the management of mixed migration flows are presented in the next section.

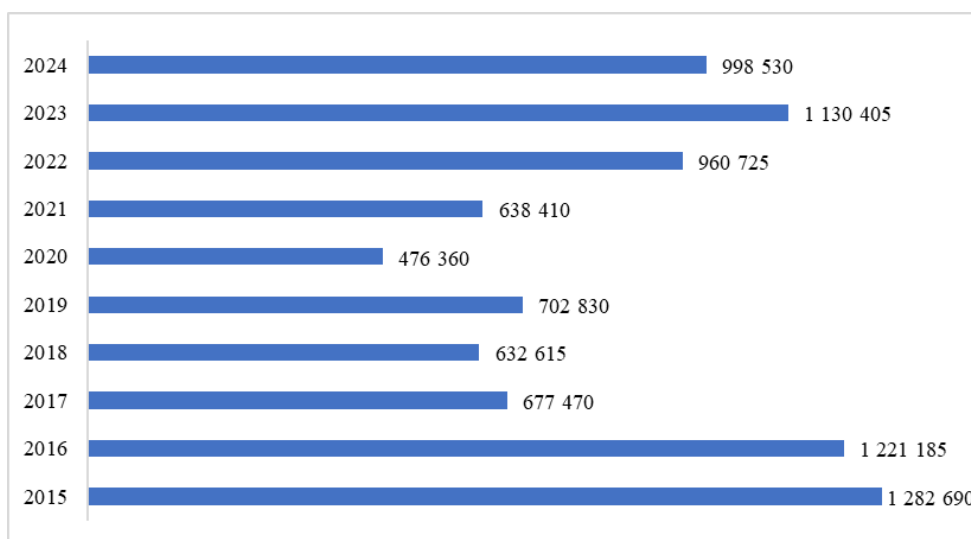


Figure 2. First-time asylum applications in the EU – 27 countries (from 2020), presented annually for the period 2015-2024 (Source: Eurostat [2])

4. Benefits and Limitations of AI Technologies in Managing Forced Migration

In the contemporary technologically advanced world, further sophisticated due to the AI era, the EU has increasingly turned to such solutions to enhance border management, as also clarified by the literature review. In addition, according to an analysis by the European Parliamentary Research Service, the EU employs AI-driven systems in fields such as: biometric identification; emotion detection; algorithmic risk assessment; and migration monitoring, data analysis, and forecasting [13]. In addition to border control protection, Frontex adds that they use drones that are equipped with advanced AI technologies such as sensors and communication systems, offering real-time surveillance that significantly enhances situational awareness [14]. These innovations reflect the EU's broader strategy to implement data-driven and intelligent decision-making processes in managing migration and ensuring border safety. However, some decisions face critique among academic society. For instance, Kontak argues that Frontex fails in its legal obligation to respect fundamental rights in relation to its biometric policy [15]

Despite growing concerns about ethical and legal risks, several good practices have been identified across the literature regarding the use of AI in migration management. First, predictive AI tools have shown potential in supporting governments by providing early estimations of refugee flows, including their timing, destination, and scale. Such tools can improve preparedness and allocation of resources, enabling more responsive and proactive migration governance [10].

Another positive application involves the integration of NLP to assist in automating administrative procedures in immigration systems. NLP can facilitate communication with asylum seekers and streamline data collection and case processing, especially in multilingual or high-volume contexts [10].

Further good practices include the use of AI-powered registration and population management systems that help document and track vulnerable groups, such as asylum seekers and displaced individuals. When properly designed, these systems can enhance operational efficiency, improve access to services, and support identification processes in humanitarian settings [8].

Importantly, several authors stress that these technologies must be implemented within transparent and rights-based accountability frameworks. Molnar highlights the need of implicating procedures to protect fundamental rights, such as privacy, freedom from discrimination, and procedural justice, particularly the right to a fair decision-maker and access to appeals mechanisms [12].

Lastly, the literature review outlines that the application of AI-based decisions in this specific field should be issued with an awareness of their inherently political nature, involving the recognition of how algorithmic systems may reflect and reinforce existing power dynamics. Thus, good practice requires incorporating participatory approaches in the design and deployment of AI tools, ensuring input from affected communities, legal experts, and civil society actors [10].

Last but not least, it should be stressed that the reviewed literature does not encompass all possible and existing applications of AI in the field of migration management; rather, it highlights selected cases and trends that have been the focus of recent academic inquiry.

5. Conclusion

The turbulent security environment, marked by many conflicts with varying intensity over the last decade, force millions of people to flee their country of origin. More often than not, forcibly displaced individuals move to safer countries, which offers them better social and economic conditions. The current analysis confirms that surges in violent conflicts directly correlate with incensements in the volume of asylum applications in the EU. In this regard, AI-based solutions have emerged as a reliable instrument in migration management systems.

By critically reviewing official institutional sources and academic literature review reviles that AI technologies, such as biometric identification, predictive analytics, and automated surveillance, just to name a few, offer substantial potential in migration management process. When properly designed and regulated, these tools can strengthen institutional capacity to forecast migration flows, optimize administrative procedures, and facilitate the protection of vulnerable populations.

This paper also highlights critical concerns related to ethics, legality, and accountability. It also becomes clear that AI application that is not enough regulated has the potential to harm some fundamental rights of migrants. Therefore, clearly defined mechanisms and well-developed legal frameworks are urgently needed for effective AI deployment.

In conclusion, while AI represents a reliable alternative for EU migration management modernization, its benefits can only be fully applied through a balanced approach. This should be done in accordance with technological innovation that respect human rights and democratic values. Last but not least, a successful integration of AI-based decisions in migration management will also generate new opportunities for business innovation, particularly in developing data-driven solutions, security technologies, and digital platforms that support sustainable and ethical migration governance.

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