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ANALYZE, CREATE, SHARE KNOWLEDGE

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Respectfully,

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MANAGING SOFTWARE PROJECTS IN THE ERA OF AI-POWERED TOOLS

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Abstract

Artificial intelligence is now a crucial component of software project management, making scheduling and task automation simpler and providing predictive analysis to aid in improved decision-making. By analyzing their early acceptance and impact through historical analysis, statistical data, and research findings, as well as their practical applications, this study investigates the impact and development of artificial intelligence-powered products. We highlight some of the industry's most important tools, their advantages and disadvantages, and some possible ramifications for upcoming initiatives. In conclusion, we demonstrate that companies that employ these technologies can benefit greatly from improved workflow, risk management, and the capacity to concentrate more on innovation as compared to their competitors.

Keywords: project management, AI tools, Jira, ClickUp, ChatGPT

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1. Introduction

1.1 Background of Software Project Management

Developing cutting-edge software is difficult and requires a controlled environment that manages time, resources, people, and costs to ensure on-time, on-budget delivery. The term software project management (SPM) refers to the planning, organizing, and leading development of software projects [1], and unlike general project management, it focuses on managing technical constraints, software lifecycles, and addressing evolving project requirements.

In today's world, the most widely used technique for project management in software teams is by far the Agile methodology, with 86% of the developers using it [2]. In fact, data shows that agile projects are 28% more successful than traditional projects [3].

Agile methodology is an adaptable and iterative approach to SPM that places a high value on user feedback and frequent short releases. Because the work is divided into short cycles called sprints, each of which focuses on certain tasks, teams are able to quickly adapt to change and continuously improve the final result.

1.2 Artificial Intelligence in Software Project Management

The creation and application of artificial intelligence (AI) in SPM has rapidly transformed the profession by providing tools that may improve workflow, automate activities, and support better decision-making. The popularity of AI has increased due to a variety of causes, such as advancements in machine learning techniques, especially in the fields of deep learning and natural language processing (NLP), data availability, and advances in processing capacity.

In today's world, AI is very widely spread and there are few websites, applications, or software services lacking some form of AI integration, such as AI-powered chat assistants or AI-enhanced search features. These tools can also be seen in most of the tools that are used in software project management.

Some of the more popular tools that are widespread include:

- ChatGPT, which was developed by OpenAI and launched in 2022, can generate human-like responses and allows users to steer the conversation to a certain style and language. This allows for the tool to be very useful for refining a project's documentation, gaining more insights into certain specific aspects of a project, or increasing the overall level of communication between teams. As of 2024, ChatGPT's website is among the top 10 most visited websites in the world [4].
- GitHub Copilot, which is similar to ChatGPT, is a code completion and automatic programming tool developed by GitHub and OpenAI that assists users by

autocompleting code, released back in 2021. A survey conducted related to the tool, in which more than 2000 developers were questioned, indicated that 88% of them feel more productive, whilst 60% noted they are more fulfilled with their jobs after starting to use GitHub Copilot [5].

- Jira, as a project management tool, integrates AI in order to improve a wide variety of features such as automating and offering smart suggestions related to tasks, offering data-driven reports and insights, and optimizing planning.
- ClickUp integrates AI-driven capabilities that streamline project management through intelligent task automation, content summarization, predictive insights, and natural language processing.

1.3 Purpose and Scope of the Paper

The purpose and scope of this paper are to understand the role of AI-powered tools in modern software project management. By analyzing how AI can potentially improve workflow, productivity, and decision-making by allowing for task automation and providing key insights, we aim to showcase the potential practical applications and benefits of most of these tools, as well as some of their downsides.

In the following sections, we will analyze the impact of AI-powered tools in the management of software projects and explore their effectiveness. The analysis will include specific areas where AI may provide measurable improvements, such as efficiency and productivity of the team, with AI automating routine tasks like scheduling, tracking project milestones, and managing resources, but also quality assurance and risk management, where AI can identify patterns in development and testing phases, flagging potential issues early on.

2. Benefits of using AI-powered tools in managing software projects

Studies by the Standish Group [6] reveal that only 35% of projects are deemed successful, with the rest often abandoned or restarted. However, the rise of AI-powered tools is set to transform project management significantly. By 2030, it's anticipated that AI (driven by big data, machine learning (ML), and natural language processing) will handle 80% of project management tasks, leading to substantial improvements in efficiency and success rates [7].

A 2023 survey conducted by Capterra [8] revealed optimistic perspectives on the integration of AI in project management. According to the findings, 77% of project management professionals viewed AI-powered tools favorably, while only 8% of organizations were opposed to the adoption of AI strategies. Key advantages highlighted included task

automation (33%), enhanced resource utilization (32%), and improved metric accuracy (27%) [9].

Selection and prioritization are a type of prediction that could be made using ML and it helps in removing human biases from the decision-making process. The project definition, planning, testing, and reporting could also be done more efficiently and less time-consuming than the traditional way of using AI.

Another strong example in the area of testing comes from a 2023 Harvard Business Review article [7] discussing the Elizabeth Line, part of the UK's Crossrail project, which required an extensive testing and commissioning process to guarantee safety and reliability. To meet these needs, the project team established the Crossrail Integration Facility, a fully automated, off-site testing center. This facility has significantly improved system efficiency, cost-effectiveness, and resilience by enabling continuous, round-the-clock audits without the risk of operator bias.

2.1 Commonly used AI-powered tools in managing software projects

The industry of developing AI-powered tools has grown significantly in recent years, reflecting the increasing demand for automation and intelligent solutions across various sectors. However, the tools that have truly revolutionized this domain are those that continue to be adopted and relied upon on a global scale.

In this section, we analyze Jira and ClickUp, even though the list could easily continue with other notable AI-powered project management tools such as Asana, Monday.com, and Trello, each offering unique features tailored to diverse team needs. We aim to do this analysis only from the point of view of what they offer in terms of AI-powered features. Additionally, platforms like Wrike, Notion, and Smartsheet are increasingly gaining traction for their innovative use of AI and flexible collaboration capabilities.

2.1.1 Jira

According to a Statista report on Atlassian's customer base, the company now serves over 300,000 customer organizations worldwide—with Jira deployed by more than 75,000 of these organizations in over 120 countries [10]. Jira is available in several languages (including English, French, German, Japanese, and Spanish), which reflects its broad international reach. Although Atlassian does not publicly disclose the exact number of individual end users, the scale of its customer base suggests that the overall user count likely exceeds tens of millions.

Furthermore, Forbes reports that Jira Service Management—a key component of Atlassian's product suite—is used by over 45,000 customers, including a significant

number of large-scale enterprises and many Fortune 100 companies [11]. These Fortune 100 organizations, which rank among the largest public and private companies in the United States by annual revenue, rely on Jira's scalable and adaptable platform to meet their complex demands.

Some of the more prominent features that have been integrated with AI offered by Jira include:

- Automation with AI: handle repetitive tasks, such as auto-assigning tickets, sending notifications, or transitioning issues based on conditions
- Smart suggestions: AI-driven recommendations to prioritize tasks, assign issues to the right team members, or identify the next best action based on project context and past behavior
- Predictive insights: Jira leverages machine learning to provide insights into project timelines, resource allocation, and risk analysis, helping teams foresee potential bottlenecks or delays
- Natural Language Processing (NLP): integrations and apps within the Atlassian ecosystem use NLP to enable intuitive task creation, such as converting conversations into actionable tasks directly from tools like Slack or Microsoft Teams
- Enhanced search capabilities: improves search functionality, offering smart filters and suggestions that make it easier to locate issues or tickets, even with vague queries
- Customizable AI bots and integrations: with tools like ChatGPT or other AI-based bots, users can automate conversation-driven workflows
- Data-driven reports and predictions.
- Anomaly detection: detect unusual patterns or outliers in team performance or project status, alerting managers to potential risks early

The utility of these AI features lies in their ability to streamline workflows and reduce manual workload. For instance, automated task assignments and real-time notifications enable teams to focus on high-value work, while predictive insights and anomaly detection help managers anticipate challenges before they escalate. Enhanced search and smart suggestions improve information retrieval, saving time and reducing errors.

However, potential downsides include the risk of over-reliance on automated processes that may misinterpret nuanced project contexts, as well as data privacy concerns and the need for regular monitoring and fine-tuning of AI integrations to ensure their accuracy and alignment with evolving business needs.

2.1.2 ClickUp

One of the most widely used AI-driven tools in project management is ClickUp, which achieved remarkable results in 2023 as it was used by over 8 million users across 1.6 million teams. In an interview with OpenView [12], Gaurav Agarwal, ClickUp's Chief Growth Officer, highlighted several factors that set the platform apart, including its comprehensive features, flexibility, integrated platform approach, user-friendly experience, and rapid development pace. Growth remains a key priority for ClickUp, with 15% of efforts dedicated to identifying new growth opportunities, 25% focused on optimizations, and the remaining 60% allocated to scaling and capitalizing on existing successes.

Some of ClickUp's AI-powered features include:

Interactive Q&A: access dynamic Q&A sessions from anywhere

- Contextual assistance: get Q&A tailored to your workspace and integrated third-party apps, as well as directly on lists and projects
- Content summarization: summarize tasks, comment threads, and documents effortlessly
- Prioritized AI responses: use wikis to organize and prioritize AI-generated answers
- AI project insights: generate project summaries with status updates, action items, and next steps
- Task automation: create subtasks automatically and streamline workflows
- automated updates: receive automatic standups and team updates
- AI workflow builder: design automation workflows using natural language
- Custom fields with AI: track summaries and progress using AI-powered custom fields
- Voice and video tools: transcribe voice and video inputs seamlessly
- Templates Library: leverage over 100 pre-built prompts and templates to jumpstart your tasks

Similarly to Jira's AI tools benefits, ClickUp also allows for streamlining projects by reducing manual effort and allowing for faster decision-making. For example, interactive Q&A and contextual assistance help team members quickly retrieve pertinent information without having to search through extensive data, while content summarization and prioritized AI responses condense lengthy discussions into actionable insights. Additionally, features like AI project insights and task automation provide real-time updates and automatically manage routine tasks, allowing teams to focus on more strategic initiatives.

3. The use of ChatGPT in software management

Generative artificial intelligence has proven to be a powerful tool at humanity's disposal, simplifying the process of information gathering. LLMs [13] which are pre-trained on a large quantity of text gathered from online sources can thus answer questions or queries provided in an understandable way, recently being capable of analyzing documents, and images and searching online for answers.

The most recognizable and widely used form of generative artificial intelligence is OpenAI's ChatGPT [14], or more generally GPT-3 and GPT-4, which has become a household name since the start of 2023 due to its extensive knowledge on most subjects. By now, tools based on GPT-3 and GPT-4 have helped users optimize their workflow through various means, however, ChatGPT is what most people use when they need to look up information or analyze data.

Relating to software project management, ChatGPT can draft documentation such as user stories or SRS, identify risks, plan sprints when using Agile methodologies [15], manage resources, or summarize useful information that the managers may need. The speed with which it can follow through with these tasks is also impressive, as it usually takes under one minute to generate a response, even less when the requirement is not complex.

3.1 Performance of ChatGPT compared to students

Boudreau performed a study [16] that compared the performance of students against a ChatGPT 3.5 model. Both the students and ChatGPT were provided a nine-page scope statement from a software project and were required to list all errors or omissions, with the students timing their work for comparison.

The study found that while the students took an average of 66.67 minutes and identified an average of 6 errors, ChatGPT identified 20 errors in less than 15 seconds. That would mean that ChatGPT was 268 times faster than the average project management student and far more accurate, though it still missed certain items.

While it is obvious that a student cannot compare with a manager with years of experience, the speed and the fact that there are even better versions of the LLM by now give ChatGPT a competitive edge when deciding whether to hire more project managers or teach them to use generative AI to become more efficient.

3.2 Adoption of ChatGPT in the project management sphere

In a recent study done by the Project Management Institute on the benefits of using generative AI in project management [17], a survey with 500 participants in two waves,

comparing high adopters of generative AI with people with various other degrees of use, has highlighted a gap in the benefits gained from using such tools.

First of all, while ChatGPT was reported as being used by more than 50% of respondents in both waves, there was a 10% decrease between them as seen in Table 1, which is a modified version of the one from the original paper. The shift to other tools such as Bard/Gemini or Copilot suggests that people have started being more informed about the options available and exploring their options more before settling on one tool.

The adoption rate seems to be one of the major factors that impact the performance boost that generative AI could provide. While individuals are interested in the benefits of using tools such as ChatGPT and have begun integrating them into their workflow, as can be seen by the 86% increase in the population of what the study calls the Trailblazer group (high adopters using AI in more than 50% of their projects), organizations have been lagging behind. The study points out that “60% of leaders expressed concern that their organization’s leadership lacks a clear plan and vision for implementing GenAI applications”, which could slow the development of the individuals as well. The results of the study are showcased in Table 1.

Tools Used	Explorers		Trailblazers	
	Wave1	Wave2	Wave1	Wave2
ChatGPT	66%	55%	67%	56%
Bard/Gemini	7%	9%	14%	22%
Copilot	15%	21%	8%	15%
Internal	11%	14%	6%	7%
Other	1%	1%	5%	1%

Table1. Percentage of different people using AITools in the study

The proficiency with which project managers use generative AI impacts the range of tasks that they can streamline with such tools, as can be seen in the survey. While simple tasks like communication, reporting and summarization do not show a significant gap, it is much more likely for AI tools to be used when completing complex tasks such as risk identification, budgeting, resource management, and data analysis in the case of the Trailblazers rather than the project managers less experienced with generative AI.

4. Statistical Analysis

In order to understand the continuously growing trend of AI-driven project management, surveys have been conducted over the course of the years 2021, 2023, and 2024 to gain insights not only into participants' knowledge and use of AI technologies at that time but also into their awareness levels and adoption across different AI applications, from machine learning to automation tools. The responses reflect both the promise and the current limitations of AI in transforming project management.

4.1 AI Knowledge, Awareness, and Adoption Trends

In 2021, during the pre-ChatGPT era, knowledge about AI in project management was limited. Of the 116 survey [18] participants (mainly from North America and Europe and primarily experienced professionals), only 3% considered themselves AI experts, while 21% admitted to having no understanding of the technology. The majority of respondents (around 50%) reported being in the early to intermediate stages of awareness, signaling a knowledge gap but also highlighting a growing curiosity. A significant 59% of respondents indicated no use of AI technologies in their workflows, citing challenges such as steep learning curves and organizational resistance. However, 45% reported limited or emerging use of AI, particularly for tasks like automation (42%), machine learning (32%), and chatbots (27%). At the time, autonomous project management tools accounted for a mere 4% of usage.

By 2023, familiarity with AI had risen sharply, reflecting both the influence of maturing tools and a broader cultural shift in embracing technological innovation. The survey, conducted with 320 participants by Peter Taylor in partnership with Capterra [8], revealed that most companies were actively using or planning to adopt AI tools. Adoption trends highlighted a focus on streamlining scheduling, progress tracking, and team management, with 80% of respondents describing their level of AI acceptance as moderate to high. Early adopters reported notable improvements in efficiency, time savings, and decision-making. These developments underscore AI's transition from an optional tool to a strategic necessity. By 2024, according to the survey made by Project.co [19], 45% of respondents reported regular use of AI tools, with strategic applications like idea generation (77%) and content creation (76%) becoming prevalent. Organizations increasingly viewed AI as integral to achieving competitive advantages and enhancing productivity.

4.2 Impact on Processes, Results, and Perceptions

As AI adoption grew, its impact on project management processes became more evident. In 2021, there was cautious optimism among professionals, with most respondents describing AI as "exciting" or "intriguing". Despite this, 78% believed project managers would remain essential, emphasizing that AI complements rather than replaces human creativity and decision-making. Several participants highlighted AI's potential to optimize repetitive tasks, improve analytics, and free project managers to focus on collaboration and emotional intelligence. However, skepticism remained regarding organizational readiness and the risk of over-reliance on technology.

By 2023, early adopters were increasingly optimistic, with 44% of respondents expressing extreme satisfaction with AI's impact. Companies reported efficiency gains and streamlined operations, and many increased their AI budgets to capitalize on AI's potential. Ethical concerns began to emerge as a key topic, with participants expressing worries about how AI systems handle sensitive data and the transparency of decision-making processes. Despite these concerns, the survey results pointed to growing confidence in AI's ability to enhance project outcomes.

In 2024, the positive trajectory continued, with 58% of respondents acknowledging AI's contribution to improved project quality and ROI. Additionally, 68% reported enhanced communication and collaboration, demonstrating AI's ability to streamline workflows and foster team efficiency. Nonetheless, uncertainty persisted, with 37% of respondents unsure about AI's measurable benefits, reflecting the complexity of evaluating its true impact in multifaceted workflows. Barriers such as ethical considerations, quality concerns, and organizational adaptation challenges remained significant but did not overshadow the optimism surrounding AI's transformative potential.

4.3 Barriers and Challenges to AI Integration

While the benefits of AI are clear, significant challenges remain. In 2021, respondents identified a lack of understanding and access to adequate tools as primary obstacles to adoption. Over half (51%) admitted to having limited knowledge about AI, and many organizations struggled with the structural and cultural shifts required for integration. By 2023, these barriers evolved to include ethical and privacy concerns, cited by 26% of participants, as well as organizational strategy gaps (28%) and the cost of implementation (25%). Respondents highlighted fears of data breaches, regulatory compliance issues, and the potential misuse of AI systems.

In 2024, these challenges persisted but showed signs of diminishing as organizations gained more experience with AI. Ethical and privacy concerns remained a significant barrier for 19% of respondents, while 22% pointed to inadequate tools and 20% to a lack of organizational strategy. These findings suggest that while the industry is making progress, achieving seamless and responsible AI integration requires sustained effort and careful

planning. These findings can be seen in Table 2, which was obtained based on sources [19][33][34].

Metrics		2021	2023	2024
Number of participants		116	320	211
AI Adoption	Not using AI	59%	8%	1%
	Limited use	27%	12%	64%
	Quite frequent use	12%	57%	
	Always using AI	N/A	23%	35%
Barriers to AI Adoption	Lack of understanding	51%	20%	51%
	Lack of adequate tools	N/A	25%	22%
	Ethical, privacy, and security concerns	N/A	26%	19%
	Lack of organizational strategy	N/A	28%	20%
Main AI application	Integration & Automation	45%	33%	59%
	Effective use of resources	N/A	32%	33%
	Project Scheduling	N/A	47%	42%
	Generate Ideas / Content	27%	N/A	77%
	Accurate Metrics	N/A	27%	30%
AI future impact	Insignificant	6%	N/A	2%
	Moderate	29%	N/A	30%
	Noteworthy	65%	N/A	68%

Table2. Percentage of people that adopted AI Tools across the years

5. Conclusions

AI-powered tools are transforming the landscape of software project management, bringing real, practical benefits like task automation, better collaboration, and smarter decision-making. Tools such as Jira, ClickUp, Asana, and ChatGPT have become essential in modern workflows, helping teams streamline operations, reduce overhead, and make decisions based on data. With the power of AI, project managers can focus on high-level strategy, fostering innovation and flexibility in an ever-changing business environment.

However, this shift isn't without its challenges. As AI becomes more integrated into workflows, it requires careful management to ensure it complements, rather than replaces, human expertise. Ethical issues, like data privacy and the transparency of AI-generated recommendations, need to be tackled head-on. For example, with tools like ChatGPT becoming more common, there are important questions about accountability and the potential risks of relying too heavily on AI for critical project decisions. Additionally, it's crucial to find a balance between AI's ability to automate and the need for human qualities in project management, such as creativity, adaptability, and emotional intelligence, which are key to long-term success.

Recent data shows that companies are becoming increasingly confident in AI's role in project management, with businesses valuing the efficiency and cost savings AI-driven tools bring. Satisfaction rates with AI tools reflect both progress and areas needing improvement, such as better alignment with existing workflows and the ability to customize tools to fit unique project needs.

The role of AI in project management is constantly evolving, unlocking new possibilities while introducing new challenges. Moving forward, organizations must invest not only in AI technologies but also in developing their teams and refining their processes. As AI platforms continue to advance, it will be essential to ensure that their use adheres to ethical standards and regulatory requirements to build trust and encourage long-term adoption.

In the end, AI-powered tools in software project management represent a major shift in how we work, offering incredible opportunities to boost efficiency, reduce risks, and achieve better results. However, to fully realize AI's potential, we need a thoughtful approach—one that blends human expertise with machine intelligence, addresses ethical concerns, and fosters a culture of continuous learning and innovation. By doing this, we can create a future for software project management that's not just technologically advanced but also deeply rooted in human values.

While AI tools have seemingly evolved in the last few years, there is much more they can achieve in terms of managing software projects. Improvements are being achieved at a fast rate and there is a push for the development of features that could replace human input entirely, such as solving complex problems, speech (both recognition and production), image vision, and motor skills for humanoid robots.

Should these innovations be achieved, a new look at the capabilities of the most relevant AI tools and respective studies about the field need to be reviewed and new studies have to be realized for an accurate representation of their effects on software project management.

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ASSESSING THE IMPACT OF AUTOMATION IN INDUSTRY

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Abstract

Automation has revolutionized industries and software development by enhancing efficiency, scalability, and quality through reduced human intervention. This paper explores the historical evolution, modern tools, and technologies that underpin automation, emphasizing their transformative impact on workflows and industrial processes. Key areas of focus include workflow management tools, version control systems, and integrated development environments, as well as their role in fostering collaboration and reducing errors.

Finally, the paper concludes with recommendations for implementing effective automation strategies, emphasizing the balance between technological efficiency and human ingenuity. Automation is presented as a key driver of innovation, enabling teams to deliver value rapidly and reliably in an increasingly digital world.

Keywords: Industrial Automation, Continuous Integration/Continuous Deployment (CI/CD), Workflow Management, Labor Economics, Technological Innovation, DevOps Practices, Distributed Teams, Socio-Technical Systems

JEL Classification: O31, O33, L86, J24, M15

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1. Introduction

Automation in industry refers to the employment of technology to perform tasks with minimum human intervention. In software development and industrial processes, automation simplifies repetitive activities, reduces errors, and increases efficiency. It allows companies to free resources for innovation and high-added-value activities by using tools and systems that execute well-defined instructions, leaving to automated workflows the execution of routine operations. Whether it be automating a manufacturing line or seamlessly deploying software updates, automation has become an indispensable pillar of modern industry. Automation tools have been on quite a journey.

Historically, automation began with mechanization during the Industrial Revolution, where machines replaced human labor for repetitive tasks. In the 20th century, the introduction of computers brought a new era that allowed industries to automate complex calculations, data storage, and communication processes. As software development kept on enhancing, so did the automation tools, from simple batch scripts to complex platforms for managing code integrations, such as CI/CD pipelines. Artificial intelligence and its sub-field of machine learning have further enhanced automation whereby tools adapt, learn from experience, and make informed decisions, hence going out of the box from fixed rules and regulations. Automation has become quite crucial in today's industrial landscape. It guarantees faster delivery cycles and quality consistency while promoting collaboration within dispersed teams.

Automation in manufacturing optimizes production lines, reduces waste, and increases safety. These tools across the board would help the scaling of operations to meet global economic demands. This enables an organization, through the automation of business processes, to unlock both operational efficiency and continuous innovation potential. As industries continue to evolve, the role of automation is set to grow, making it a cornerstone of progress in the digital age. This essay will go on to explore the different kinds of tools and technologies that drive automation, their importance, and how they transform workflows across industries.

The discussion extends to programming languages and building automation tools, highlighting their impact on managing complex projects. Automation in Linux environments, using tools such as Docker, Kubernetes, and Ansible, is examined for its role in infrastructure management and container orchestration. Additionally, the integration of continuous integration and deployment (CI/CD) tools is analyzed as a cornerstone of modern development pipelines.

The paper underscores the importance of automated testing and quality assurance in ensuring software reliability. Challenges in global workflows, such as asynchronous collaboration and conflict resolution, are addressed alongside emerging trends in AI and machine learning, which are poised to redefine the future of automation. Brabete et al. [1]

show that the current European information and communications technology (ICT) sector follows a growing trend, which proves the need for modern workflow management solutions to accommodate larger teams and increasingly complex projects in the ICT industry.

2. Workflow Management Tools

Workflow management tools are essential for organizing tasks, tracking progress, and improving collaboration within teams. Tools like Jira, Trello, and Polarion have become industry standards for project management. These tools not only streamline workflows but also enhance traceability, ensuring that every task is documented and linked to project milestones.

2.1 Survey Insights

From the survey conducted [2], Jira emerged as the most widely used tool, with respondents rating its efficiency highly across key metrics:

- The volume of tasks completed on time: Over 80% of respondents gave Jira 4 stars or 5 stars, highlighting its ability to facilitate timely delivery of tasks.
- Frequency of changes in planning: While flexibility was noted, scores were slightly lower (average of 3 stars), indicating room for improvement in dynamic environments.
- Sprint completion rates: Rated at 4 stars on average, indicating that Jira supports consistent sprint progress.

Jira's ability to integrate with other tools like CI/CD pipelines and version control systems was a recurring theme in the responses, demonstrating its role in creating a seamless development environment.

Globally distributed teams benefit significantly from such tools. As noted in the survey, organizations with teams spread across different time zones leverage Jira to maintain a unified view of project progress. This minimizes miscommunication and ensures continuity in workflows. For instance, developers in one region can update tasks at the end of their day, allowing colleagues in other time zones to pick up seamlessly. The benefits of ticket management tools include:

- Improved traceability: Every task is documented and linked to its origin, making it easy to track dependencies and resolve issues.
- Enhanced collaboration: Teams can share updates, comments, and progress, reducing the need for constant synchronous communication.

- **Increased efficiency:** By automating notifications, updates, and reports, these tools save time and reduce administrative overhead.

In conclusion, workflow management tools are indispensable for modern teams, particularly in environments where collaboration and rapid iteration are key. The survey results reaffirm the value these tools bring, particularly in large, globally distributed organizations.

3. Version Control Systems

In the fast-paced world of software development, version control systems (VCS) like GitHub, GitLab, and Bitbucket serve as the cornerstone of collaboration and stability. These tools not only manage code but also facilitate teamwork, ensuring that developers can work on the same project, no matter where in the world they are.

3.1. Overview of Version Control Tools: GitHub, GitLab, Bitbucket

GitHub is synonymous with open-source development and community collaboration. Its pull request (PR) system, inline code reviews, and deep integrations with automation tools make it a favorite among developers. Meanwhile, GitLab offers an all-in-one solution by bundling VCS with CI/CD pipelines, allowing teams to manage development and deployment workflows in one place. On the other hand, Bitbucket, as part of the Atlassian suite, excels in environments where traceability is key, integrating seamlessly with Jira for enhanced project tracking.

These tools are critical not just for writing and storing code but for building cohesive workflows that allow teams to innovate while minimizing errors and duplication.

3.2. The Role of Version Control in Collaboration and Software Stability

Version control systems are indispensable for managing the complexities of collaboration, particularly in large, globally distributed teams. They allow developers to work on separate features simultaneously, without worrying about overwriting each other's work. This is particularly critical in global teams, where development operates as a 24-hour cycle. When one team clocks out in Singapore, another in San Francisco takes over seamlessly, thanks to shared repositories and synchronized workflows.

However, this level of collaboration also introduces challenges unique to large organizations. In smaller teams, where tasks are often isolated and linear, compatibility issues or merge conflicts are rare. But in larger teams, where dozens of developers may

work on interconnected features, the risk of integration problems increases exponentially. This is where the real power of version control shines, by tracking every change, maintaining a history of revisions, and integrating automated testing.

Stability is equally crucial. A feature that works perfectly on its own may clash with another when merged into the main branch. Automated tools help catch these conflicts early, but in large systems, even the smallest oversight can snowball into significant issues. Version control tools paired with CI/CD pipelines ensure these problems are addressed before they reach production.

3.3. Branching Strategies, Code Reviews, and Continuous Commits in Large Organizations

In large organizations, branching strategies are essential for managing the scale and complexity of development projects. Common strategies include:

- Feature branches, where new functionality is isolated until it's ready for production.
- Release branches, ensuring production code remains stable while accommodating hotfixes.
- Trunk-based development, which promotes frequent commits directly to the main branch, minimizing the lifespan of branches and reducing merge conflicts.

Code reviews are an integral part of maintaining software quality in such environments. They enable team members to evaluate each other's work, offering a layer of oversight and shared accountability. But even with thorough reviews, passing a pull request (PR) doesn't guarantee success. A commit may work perfectly in isolation but could conflict with another when integrated. For this reason, large organizations rely on continuous integration (CI) and continuous deployment (CD) pipelines, which automatically test and validate the entire application after every merge.

Continuous deployment ensures a rapid feedback loop and successful builds are automatically pushed to staging or production environments, enabling faster delivery cycles. This automation is particularly valuable in distributed teams, where maintaining synchronization across continents is a constant challenge. A developer in Europe might commit code at the end of their day, only for a colleague in Asia to encounter and resolve an issue by the time Europe wakes up. This cycle of continuous commits and validation keeps progress steady and predictable.

3.4. The Unique Challenges of Large Teams

The complexities described above are primarily the domain of large organizations. In smaller teams, where development is less interdependent, the risk of compatibility issues

or merge conflicts is significantly lower. Developers in small teams often work on isolated tasks, and there's less overlap in code. However, in organizations with hundreds of contributors, where every feature impacts others, these challenges are inevitable.

For example, imagine two teams in different time zones working on the same project. One team finishes a feature and merges it into the main branch. The other team, unaware of these changes, merges their own feature, creating a conflict that breaks the application. Such situations are rare in small teams but common in large ones, underscoring the importance of robust VCS systems paired with automation pipelines.

The experiences of large companies are particularly relevant here. They provide valuable insights into scaling processes, handling conflicts, and integrating automation to maintain stability. For smaller teams aiming to grow, adopting the practices of these organizations, like implementing branching strategies and CI/CD pipelines, can prepare them for future challenges.

By emphasizing the unique challenges faced by large organizations and the lessons they provide, this section underscores the broader relevance of VCS tools. Whether you're in a small team or a multinational corporation, the principles of effective version control and automation remain essential for long-term success.

4. Integrated Development Environments (IDEs)

Integrated Development Environments (IDEs) serve as the central workspace for developers, combining tools for writing, debugging, and testing code. Whether free or paid, IDEs significantly influence a team's productivity and the quality of the software they produce. Popular options such as Visual Studio, JetBrains IntelliJ and PyCharm, and Eclipse dominate the market, each offering unique strengths tailored to different languages, projects, and organizational needs.

4.1. Overview of Popular IDEs: Visual Studio Community vs Paid, JetBrains IntelliJ and PyCharm, Eclipse

Visual Studio: Bridging Accessibility with Advanced Features

Visual Studio, developed by Microsoft, provides a comprehensive range of tools for developers, from individual coders to large enterprise teams. Its Community Edition is free and accessible to students, small teams, and open-source contributors. Despite being free, it supports multiple programming languages such as C#, Python, and C++ and offers features like intelligent code completion, debugging, and Git integration. Notably,

developers can connect GitHub Copilot to the Community Edition, leveraging AI-powered coding assistance to generate code suggestions in real-time.

For more complex projects, the Professional and Enterprise Editions offer advanced tools like IntelliCode, performance profiling, and robust testing capabilities. Visual Studio IntelliCode, in particular, is a standout feature in team environments. As noted, "Best for Team Projects, Visual Studio IntelliCode tends to shine in environments where teamwork and consistency are key. With its smart suggestions tailored to specific coding styles and its ability to use shared knowledge, IntelliCode can greatly enhance collaborative coding efforts." [3] These capabilities ensure that teams maintain consistent coding standards while improving productivity in collaborative settings.

Additionally, Visual Studio Code (VS Code) deserves mention. While not a full IDE, its lightweight design and extensive plugin ecosystem allow it to rival traditional IDEs. Features like debugging, Git integration, and CI/CD management through extensions make it a modular and flexible choice for developers.

By offering both the full-featured Visual Studio and the extensible VS Code, Microsoft empowers developers across various needs, from solo projects to complex, collaborative enterprise solutions.

JetBrains IntelliJ and PyCharm

JetBrains IntelliJ and PyCharm are part of a suite of highly specialized IDEs designed to streamline development in specific programming languages. IntelliJ excels in Java projects, offering robust tools for productivity and code quality, while PyCharm is widely regarded as the gold standard for Python development due to its tailored features for Python-specific workflows. Both IDEs integrate deeply with version control systems such as Git, Subversion, and Mercurial, enabling seamless collaboration and code management [4]. Additionally, they support integration with Continuous Integration and Continuous Deployment (CI/CD) pipelines, enhancing automated workflows and ensuring efficient development cycles [5].

The JetBrains suite operates on a subscription-based model with options suitable for individuals, startups, and enterprises, making it adaptable to various scales of development teams and projects. These features make IntelliJ IDEA and PyCharm invaluable for developers working on large-scale, automated workflows.

PyCharm vs VS Code: Key Differences

Both PyCharm and VS Code are highly popular tools for programmers. In fact, according to the Python Developers Survey 2022 conducted by JetBrains, two-thirds of respondents chose PyCharm and VS Code as the top two IDEs for Python development [6]. This demonstrates the dominance of these tools in the Python ecosystem, with PyCharm

offering advanced, Python-specific capabilities, while VS Code provides flexibility through its extensive plugin ecosystem.

Eclipse: A Flexible Powerhouse for Developers

Eclipse, an open-source Integrated Development Environment (IDE), has long been a favorite among Java developers and extends its capabilities to numerous other programming languages through its extensive plugin ecosystem. This adaptability allows developers to customize their environment, making Eclipse a versatile choice for projects ranging from basic Java applications to complex, multi-language systems [7].

While Eclipse may lack the sleek user interfaces and advanced features of some paid alternatives, its open-source nature is a significant advantage. Developers have full control over their environment, and the global Eclipse community ensures a constant stream of updates, plugins, and support. This makes Eclipse a reliable and flexible solution for budget-conscious teams that don't compromise on power [8].

Eclipse is particularly appealing to educational institutions and startups, offering robust tools for debugging, testing, and version control integration, all at no cost. Its compatibility with enterprise frameworks and tools further enhances its value for companies seeking a scalable, cost-effective development environment [9]. For developers who enjoy fine-tuning their tools or value the open-source philosophy, Eclipse represents a statement of independence and ingenuity.

4.2. Free vs Paid IDEs: Comparison and Productivity

The choice between free and paid IDEs often hinges on team size, project complexity, and budget. Free IDEs like Visual Studio Community and Eclipse offer robust features for smaller teams and open-source projects. They provide essential tools like code editing, debugging, and basic plugin support without incurring additional costs.

However, as projects scale, the limitations of free IDEs become apparent. Paid IDEs like JetBrains IntelliJ or Visual Studio Enterprise provide advanced features such as:

- AI-powered suggestions: IntelliCode in Visual Studio or JetBrains Code With Me improves developer productivity by predicting the next steps and suggesting code snippets.
- Enterprise-level integrations: Paid versions often include seamless support for complex version control systems, CI/CD pipelines, and cloud deployments.
- Enhanced debugging tools: These IDEs offer powerful profiling and debugging features that help identify and resolve performance bottlenecks more efficiently.

In large organizations, these premium features can save significant time and resources, justifying the cost. For example, teams working on complex systems often rely on

automated code refactoring to maintain consistency across large codebases, a feature more developed in paid IDEs.

4.3. Automation Enhancing Features: Code Completion, Debugging, and Plugin Ecosystems

Modern IDEs are built with automation at their core, offering features that reduce repetitive tasks and streamline the development process:

- **Code Completion:** All major IDEs provide intelligent code completion, which speeds up coding by suggesting methods, classes, and variables. Tools like IntelliCode in Visual Studio take this a step further, using machine learning to recommend contextually relevant code snippets.
- **Debugging Tools:** Advanced debugging capabilities are essential for maintaining code quality. JetBrains IDEs and Visual Studio provide visual interfaces for step-by-step debugging, memory inspection, and performance profiling, making it easier to identify and fix bugs.
- **Plugin Ecosystems:** Plugins extend the functionality of IDEs, integrating tools like Docker, Kubernetes, and Git directly into the development environment. For example, developers can manage containers, push commits, and monitor CI/CD pipelines without leaving the IDE.

The role of these features becomes even more critical in global, distributed teams, where seamless integration and automation ensure consistency and productivity. A developer in Europe can commit code refactored with PyCharm, confident that their formatting and structure align with team standards in Asia or the Americas. Plugins that automate testing, deployment, and version control ensure that all code adheres to organizational policies, regardless of who wrote it.

The Human Element of IDE Selection

While technical features are critical, the human factor cannot be ignored when selecting an IDE. Developers often gravitate toward tools they find intuitive and enjoyable to use, which can have a tangible impact on productivity and job satisfaction. For instance:

- A team working on cross-platform projects might prefer JetBrains IntelliJ for its ability to integrate with every part of the development pipeline.
- A small startup with limited resources might choose Visual Studio Community, valuing its comprehensive features despite being free.
- An open-source contributor may rely on Eclipse, appreciating its community-driven nature and extensive plugin library.

These decisions go beyond functionality, they shape how teams collaborate, innovate, and scale.

Interconnectedness with Broader Automation

The relevance of IDEs to automation lies in their ability to connect with other tools and processes:

- IDEs integrate with version control systems, allowing developers to commit, merge, and resolve conflicts without switching environments.
- Features like automated refactoring and error detection directly contribute to smoother workflows in CI/CD pipelines.
- Debugging tools reduce the risk of conflicts during global deployments, a recurring challenge in large organizations.

Ultimately, IDEs are not just tools but enablers of innovation, ensuring that developers can focus on creative problem-solving while automation handles the repetitive details. Whether in a small team or a global enterprise, the right IDE can transform the development process, blending human ingenuity with technological efficiency.

5. Programming Languages and Automation Tools

Programming languages and their associated tools form the backbone of software development automation. The distinct characteristics of each language influence the choice of automation tools and workflows, impacting how large-scale projects are managed. Tools like Makefiles, CMake, Gradle, and Maven simplify development by automating build processes and ensuring cross-platform compatibility [10].

5.1. C vs C++ vs Java vs Python: Strengths, Weaknesses, and Typical Use Cases

- **C:** A foundational language, C is prized for its simplicity and ability to interface directly with hardware. It is extensively used in systems programming, embedded systems, and scenarios where performance is critical. Despite its efficiency, C's lack of modern abstractions and reliance on manual memory management make it prone to bugs, requiring careful debugging. IDEs like Visual Studio and Eclipse often accompany C development for their static analysis and debugging capabilities [7].
- **C++:** Building on the structure of C, C++ introduces object-oriented programming and more advanced features, making it ideal for game development, real-time simulations, and performance-heavy applications. However, its complexity can pose challenges, particularly when dealing with pointers, templates, and memory management. CMake

is a go-to tool in the C++ ecosystem, simplifying cross-platform builds by abstracting platform-specific details. Developers can create build configurations that seamlessly work on Windows, Linux, and macOS, enhancing project portability and scalability [10].

- **Java:** Java's strength lies in its portability, achieved through the Java Virtual Machine (JVM). It dominates enterprise application development, mobile (Android) apps, and backend systems. Paired with build automation tools like Gradle and Maven, Java projects benefit from automated dependency resolution, consistent builds, and extensive plugin ecosystems. IntelliJ IDEA further streamlines Java development with its intelligent coding features and deep integration with version control and CI/CD pipelines [11].
- **Python:** Known for its simplicity and versatility, Python is widely used in automation, scripting, data science, and machine learning. Its interpreted nature makes it slower for performance-critical applications but unmatched for prototyping and development speed. IDEs like PyCharm and Visual Studio Code enhance Python's capabilities with integrated tools for testing, debugging, and CI/CD workflows, making it a go-to choice for DevOps and automation-focused tasks [6].

5.2. Tools for Build Automation: Makefiles, CMake, Gradle, Maven

- **Makefiles:** As one of the oldest build tools, Makefiles are simple and efficient for small-scale projects, especially in C and C++ development. Developers manually define dependencies and rules for compilation, making Makefiles both powerful and, at times, challenging to manage in larger, more complex projects [10].
- **CMake:** A modern alternative to Makefiles, CMake abstracts platform-specific intricacies, enabling developers to write portable build scripts. Particularly popular in the C++ community, CMake generates native build files (like Makefiles, Visual Studio projects, or Ninja build files), allowing code to compile seamlessly across multiple operating systems. For instance, a large-scale application with modules running on Linux and Windows can leverage CMake to ensure consistent builds, reducing the risk of environment-specific bugs [10].
- **Gradle:** Designed for Java and Kotlin ecosystems, Gradle is a highly flexible build automation tool that focuses on speed and scalability. Its declarative Domain-Specific Language (DSL) for scripting allows developers to define tasks efficiently, while its incremental build system reduces compilation time. Gradle's seamless integration with CI/CD pipelines and its ability to manage dependencies make it a favorite for large-scale, multi-module projects [11].
- **Maven:** Maven, another cornerstone of Java development, emphasizes convention over configuration, reducing the need for complex scripting. Its dependency management system ensures that all libraries and plugins are resolved automatically, simplifying

version conflicts. Maven is particularly favored in enterprise environments for its robust plugin ecosystem, which supports tasks like testing, packaging, and deployment. Large organizations rely on Maven to maintain consistency across development and production environments [11].

5.3. Cross-Platform Build Automation and Its Impact on Large-Scale Projects

As software systems grow in complexity, cross-platform compatibility becomes a necessity. Automation tools like CMake, Gradle, and Maven play a critical role in ensuring that code written for one environment compiles and functions consistently across others.

For example, CMake is invaluable in large-scale projects where components must run on multiple operating systems. Developers can define platform-agnostic build configurations, allowing teams in different regions, using Windows in the US and Linux in Europe, to contribute to the same codebase without compatibility issues. This simplifies collaborative workflows and ensures reliability [10].

In Java-based ecosystems, Gradle and Maven streamline dependency management and build processes. These tools allow developers to focus on writing code while automating tasks like resolving library conflicts, building artifacts, and running tests. When integrated with CI/CD systems like Jenkins or GitLab CI, they enable continuous builds, ensuring that every commit is automatically tested and deployed. This is especially critical in globally distributed teams, where automation bridges the gap between time zones [11].

6. Automation In Linux Environments

Linux is the backbone of many automation workflows due to its flexibility, open-source nature, and extensive ecosystem of tools and scripting capabilities. It supports both free and commercial distributions, each suited to specific use cases, and offers a variety of automation tools for managing tasks, configurations, and deployments.

6.1. Free vs Commercial Distributions: Red Hat vs CentOS vs Fedora

Linux distributions come in various forms, ranging from community-driven free distributions to commercially supported enterprise-grade solutions.

- **Red Hat Enterprise Linux (RHEL):** RHEL is a commercial distribution designed for enterprise environments. It offers long-term support, security updates, and enterprise-level features like integrated performance monitoring tools and container orchestration support. RHEL is known for its stability and is widely used in production environments

where downtime must be minimized. Red Hat also provides official support and certifications, making it a go-to choice for businesses that need reliable, tested solutions [12].

- CentOS: CentOS was historically a free and open-source counterpart to RHEL, built from the same source code. While it lacked official support, it offered nearly identical functionality, making it ideal for those who wanted enterprise-grade features without the cost. However, the shift to CentOS Stream as an upstream development platform for RHEL has made it more dynamic and less suitable for production environments [13].
- Fedora: Fedora is a cutting-edge, community-driven distribution that serves as a testing ground for RHEL. It includes the latest software and innovations, making it ideal for developers and those who need access to the newest features. However, its short life cycle and frequent updates make it less stable for production use [13].

6.2. Automating Tasks with Shell Scripting, Ansible, Puppet, and Chef

Linux's flexibility is amplified by its powerful automation capabilities, making it a preferred platform for managing tasks, infrastructure, and deployments.

- Shell Scripting: Shell scripting is the most basic form of automation in Linux, allowing developers to write scripts that automate repetitive tasks such as file manipulation, system monitoring, and backups. Bash, the most common shell, supports logic, loops, and conditionals, enabling robust and versatile scripts. Shell scripts are easy to create but can become difficult to manage in large or complex environments [14].
- Ansible: Ansible is an open-source automation tool that simplifies configuration management, application deployment, and task automation. It uses a simple YAML-based language to define tasks and is agentless, meaning it doesn't require additional software installed on target machines. Ansible's modular approach makes it ideal for automating infrastructure tasks across multiple systems, such as provisioning servers or deploying applications consistently [15].
- Puppet: Puppet is a configuration management tool that defines the desired state of a system using a declarative language. It uses a master-agent architecture to ensure systems conform to specified configurations. Puppet is commonly used in enterprise environments for tasks such as managing system updates, enforcing security policies, and configuring network settings [15].
- Chef: Chef is another popular configuration management tool that uses a Ruby-based DSL to define infrastructure as code. It is particularly suited for environments requiring complex configurations or frequent changes. Chef supports both on-premises and cloud-based environments, making it a flexible choice for hybrid infrastructure [15].

6.3. Docker and Kubernetes: Containerization and Orchestration for Automated Deployments

Containerization has revolutionized how applications are deployed and managed, and tools like Docker and Kubernetes have become indispensable for modern development workflows.

- **Docker:** Docker enables developers to package applications and their dependencies into lightweight, portable containers. These containers run consistently across different environments, from development to testing to production. This eliminates the “it works on my machine” problem and ensures that software behaves predictably regardless of where it is deployed. Docker also integrates with CI/CD pipelines, making it easy to automate the building, testing, and deployment of containerized applications [16].
- **Kubernetes:** Kubernetes, often abbreviated as K8s, is a powerful open-source platform for orchestrating containerized applications. It automates tasks such as:
 - Deployment of containers across clusters.
 - Scaling applications based on demand.
 - Managing container networking and storage.
 - Monitoring application health and self-healing in case of failure.

Kubernetes is particularly useful for managing microservices architectures, where applications are broken down into smaller, independent services that communicate with each other. By automating the orchestration of containers, Kubernetes ensures high availability, reliability, and scalability [17].

The combination of Docker and Kubernetes allows teams to achieve seamless and automated deployments, enabling faster delivery cycles and more efficient resource utilization.

Integrating Automation in Linux Workflows

Linux distributions, coupled with automation tools, provide a seamless workflow across development, testing, and production environments. For example:

- A company using RHEL might automate its infrastructure with Ansible and deploy containerized applications using Docker.
- A team experimenting with Fedora could use Kubernetes to scale microservices across clusters.
- Shell scripts can handle quick, custom tasks, while tools like Puppet ensure long-term configuration stability.

This ecosystem reduces manual effort, ensures consistency, and enables scalable, reliable solutions across diverse environments.

7. Continuous Integration and Continuous Deployment

Continuous Integration (CI) and Continuous Deployment (CD) have become cornerstones of modern software development. These practices rely on tools that automate and streamline the testing, building, and deployment processes, ensuring rapid feedback and high-quality releases. In distributed teams, where developers work across time zones, CI/CD tools are not just helpful, they are vital for maintaining efficiency and collaboration.

7.1. Overview of Jenkins, Bamboo, and Other CI/CD Tools

- **Jenkins:** Jenkins is an open-source CI/CD tool known for its extensibility and strong community support. It allows developers to automate everything from code integration to deployment. With over 1,800 plugins, Jenkins can be customized for virtually any workflow, including integration with Docker, Kubernetes, and Git repositories. Its flexibility makes it a popular choice in both small startups and large enterprises [18].
- **Bamboo:** Bamboo, developed by Atlassian, offers out-of-the-box integration with the Atlassian ecosystem, including Jira and Bitbucket. Unlike Jenkins, Bamboo is a paid solution, but its streamlined setup and prebuilt functionality make it a strong contender for teams already using Atlassian products. Bamboo excels in managing parallel builds and supports Docker and AWS environments, making it ideal for scaling complex CI/CD pipelines [19].
- **GitLab CI/CD:** Built directly into GitLab, this tool provides a seamless experience for teams using GitLab repositories. It supports YAML-based pipeline definitions and integrates CI/CD into every stage of development, from merge requests to deployments. Its simplicity and native integration make it especially appealing for teams that prioritize cohesion in their tooling [20].

Other notable tools include CircleCI, Travis CI, and TeamCity, each catering to specific needs like cloud-based pipelines, containerized builds, or enterprise-level scalability. The choice of tool often depends on the team's existing infrastructure, project complexity, and budget.

7.2. Creating Pipelines for Automated Testing, Build, and Deployment

At the heart of CI/CD workflows are pipelines, which automate the repetitive tasks of building, testing, and deploying code. A typical CI/CD pipeline consists of the following stages:

- **Build:** Converts source code into executable artifacts. Tools like Gradle, Maven, and Docker often play a role here.

- **Test:** Run automated tests, including unit, integration, and end-to-end tests. Tools like JUnit, pytest, and Selenium are integrated to ensure code quality.
- **Deploy:** Moves tested artifacts to staging or production environments. Tools like Ansible, Kubernetes, and Docker orchestrate deployments.

Creating these pipelines involves defining tasks in configuration files (e.g., Jenkinsfiles for Jenkins, YAML files for GitLab CI/CD). These pipelines ensure that every code change is automatically tested and built, significantly reducing the time developers spend on manual processes [21].

7.3. Continuous Feedback Within Distributed Teams and Fast Iteration Cycles

CI/CD tools are the backbone of modern distributed development. In globally dispersed teams, where work is handed off across time zones, CI/CD ensures that developers can work asynchronously while maintaining a unified codebase. For example:

- A developer in Asia commits changes to a Git repository. The CI pipeline automatically triggers a build and runs tests.
- By the time developers in Europe start their day, the results of the tests are available. If the tests fail, the team is notified, enabling immediate fixes.

This continuous feedback loop is critical for identifying and addressing issues early in the development cycle, preventing costly delays or rollbacks in production.

In fast-paced development environments, CI/CD tools also enable rapid iteration cycles. Features like canary deployments (deploying updates to a small subset of users before full release) and blue-green deployments (switching between two production environments) allow teams to deploy new features safely and efficiently [22].

The Dependence on CI/CD: A Philosophical Perspective

The dependence on CI/CD tools reflects the changing nature of work in software development. The industry has moved from long release cycles to continuous delivery, where new features and updates are expected to roll out regularly. This shift demands not only technical tools but also a cultural commitment to automation and quality.

Without CI/CD, modern development workflows would crumble under the weight of manual testing, delayed feedback, and inconsistent deployments. These tools are not merely conveniences, they are the glue that holds distributed teams together, enabling them to deliver value to users at an unprecedented pace.

As development environments grow more complex, with microservices, containerization, and multi-cloud architectures, the role of CI/CD becomes even more vital. CI/CD is no longer optional; it's the foundation of reliable, scalable, and efficient software delivery. It embodies the philosophy that quality is a continuous process, not an afterthought.

8. Automated Testing and Quality Assurance

Automated testing and quality assurance (QA) are pivotal components of modern software development. As development workflows evolve toward faster delivery cycles and distributed teams, automated testing ensures that code remains reliable, maintainable, and scalable. The integration of various types of testing and frameworks into CI/CD pipelines enables continuous testing, which has redefined how software quality is maintained.

8.1 Types of Automated Testing: Unit Testing, Integration Testing, Regression Testing

- **Unit Testing:** Unit tests validate individual components or functions of a codebase in isolation. These tests are highly specific, fast to execute, and provide the first line of defense against bugs. For instance, testing whether a function correctly adds two numbers ensures that the smallest units of the application work as intended [23].
- **Integration Testing:** Integration tests examine how different modules or services interact with each other. They ensure that the integrated components of an application function cohesively. For example, in a microservices architecture, integration tests check the communication between services via APIs or message queues [24].
- **Regression Testing:** Regression tests ensure that recent code changes do not break existing functionality. This is particularly critical in fast-paced development environments where frequent commits and updates can inadvertently introduce issues into unrelated parts of the application. Automated regression tests save time and resources compared to manual testing, especially in large applications with extensive feature sets [25].

8.2. Test Frameworks: JUnit, pytest, Google Test, NUnit

- **JUnit:** A widely used framework for unit testing in Java, JUnit integrates seamlessly with CI/CD pipelines. It supports annotations and assertions, simplifying test writing and maintenance. JUnit is often used alongside tools like Maven and Gradle to automate test execution during builds [26].
- **pytest:** Popular in the Python ecosystem, pytest is known for its simplicity and scalability. Its support for fixtures, plugins, and parameterized testing makes it ideal for a wide range of use cases, from simple unit tests to complex functional tests. Pytest is highly extensible and integrates well with CI/CD pipelines [27].
- **Google Test:** A robust C++ testing framework, Google Test is designed for both unit and integration testing. It supports parameterized tests, custom assertions, and mocking,

making it suitable for large-scale C++ applications. Google Test's compatibility with CMake ensures seamless integration into build systems [28].

- NUnit: A popular testing framework for .NET languages, NUnit provides powerful tools for writing and executing tests. Its attribute-based syntax makes it user-friendly, and it integrates smoothly with tools like Azure DevOps and Jenkins, enhancing its utility in enterprise environments [29].

8.3. Continuous Testing to Ensure Software Quality

Continuous testing integrates automated testing into every stage of the development pipeline, ensuring that quality is continuously validated. This approach goes beyond traditional testing paradigms, embedding QA into the workflow from the earliest stages of development.

- Real-Time Feedback: Continuous testing provides immediate feedback on the quality of code changes. For instance, a developer pushing a commit triggers automated tests, which catch bugs or regressions before the code merges into the main branch. This reduces the cost of fixing defects, as issues are identified early in the development cycle [30].
- Scalability and Complexity Management: Continuous testing is particularly vital in large, distributed systems where numerous components interact. Automated tests ensure that new features or updates do not compromise the stability of the entire application, enabling organizations to scale their workflows confidently.
- Integration with CI/CD Pipelines: Continuous testing works hand-in-hand with CI/CD tools like Jenkins and GitLab CI/CD, ensuring that testing occurs automatically after every build. This integration allows teams to maintain high release velocity without sacrificing quality [20][31].

The Vital Role of Automated Testing in Workflow Evolution

Automated testing is not merely a tool but a cultural shift in software development. It embodies the principle of shift-left testing, where QA begins early in the development lifecycle. This proactive approach has transformed workflows, enabling faster iterations, better collaboration, and higher reliability.

The evolution of automated testing and continuous testing frameworks has been unprecedented. Decades ago, testing was a manual, labor-intensive process that often delayed releases. Today, with tools like JUnit, pytest, and Jenkins, testing is integrated into every aspect of development. This shift has redefined the relationship between developers and QA teams, fostering a more collaborative and iterative workflow.

Without automated testing, the speed and complexity of modern software development would be unmanageable. Automated tests act as a safety net, allowing developers to

innovate rapidly while maintaining confidence in their code. As organizations increasingly adopt microservices, containerization, and distributed architectures, the importance of automated testing will only grow.

9. Challenges and Opportunities in Global Workflows

In the interconnected world of modern software development, global workflows are both a necessity and a challenge. Teams scattered across continents work on shared codebases, pushing continuous commits, resolving conflicts asynchronously, and striving to maintain consistency. These workflows are a testament to human ingenuity and a reminder of the fragility of synchronized collaboration. Like the butterfly effect in chaos theory, a small, seemingly inconsequential change can ripple through a system, creating cascading challenges, or breakthroughs.

9.1. Continuous Commits and Collaboration Across Time Zones

The beauty of global workflows lies in their continuity. When one team ends its day in Tokyo, another begins its shift in San Francisco. Continuous commits enable a seamless transition, ensuring that work progresses around the clock. However, this constant motion introduces the challenge of synchronization.

A single commit, while functional in isolation, can interact unpredictably with changes from other teams. For example, a developer in Europe might update a dependency in a shared library, unaware that a team in India has built a new feature relying on the old version. Without automated testing pipelines and conflict resolution tools, such situations could disrupt entire systems [32].

Even with tools like Git, Jenkins, and CI/CD pipelines, global workflows rely on constant vigilance. There's always an infinitesimally small chance, like the proverbial butterfly flapping its wings, that something could go wrong, creating a domino effect that escalates into a critical issue. This reality underscores the need for robust automation and clear communication protocols.

9.2. Asynchronous Code Reviews and Conflict Resolution Tools

Asynchronous workflows are the backbone of global collaboration. Code reviews, conducted across time zones, allow developers to ensure quality and consistency without requiring simultaneous engagement. However, these workflows introduce delays and potential miscommunications.

Tools like GitHub, GitLab, and Bitbucket provide platforms for asynchronous reviews, enabling inline comments, approval workflows, and discussion threads. However, these tools can only do so much. Human factors, like differing interpretations of a comment or oversight during a review, introduce complexity. For instance:

- A misinterpreted suggestion could lead to an unexpected change in functionality.
- A missed dependency update could cause failures in another module.

Conflict resolution tools like merge conflict detection and three-way merges mitigate these challenges, but they cannot eliminate them entirely. There's always a risk that resolving one conflict might introduce another, thus reinforcing the need for clear communication and automated testing at every stage [33].

9.3. Best Practices for Maintaining a Single Repository Across Continents

Maintaining a single, unified repository across continents requires a combination of technical rigor and cultural adaptation. Best practices include:

- **Clear Commit Standards:** Establishing naming conventions, detailed commit messages, and branch organization ensures that everyone on the team understands the history and intent of changes [34].
- **Automation:** Integrating tools like CI/CD pipelines ensures that every commit is automatically tested, reducing the chance of introducing errors. Continuous deployment models provide immediate feedback and prevent broken code from propagating.
- **Time Zone Awareness:** Scheduling overlapping hours for critical meetings or synchronizations can help mitigate communication gaps. Tools like Slack, Jira, and Confluence enhance asynchronous communication, ensuring transparency and accountability.
- **Feature Flags:** Using feature flags allows teams to ship incomplete or partially functional features, enabling continuous delivery while keeping unfinished work dormant in production [35].
- **Frequent Merges:** Encouraging frequent merging of branches into the mainline prevents long-lived branches from diverging significantly, which minimizes merge conflicts and ensures repository consistency.

The Vital Role of Chaos Management

The chaos theory's butterfly effect [36] is an apt metaphor for global workflows. A single, small change (an untested commit, a misunderstood review, or an outdated dependency) can propagate through a system, resulting in significant disruptions. In this context, automation acts as a stabilizing force, reducing the unpredictability inherent in human collaboration.

However, automation alone cannot eliminate chaos. The human factor (creativity, intuition, and communication) is irreplaceable. It's the balance between structure and flexibility, between automation and human insight, that allows global workflows to thrive. Just as a chaotic system can create disorder, it can also yield innovation and breakthroughs. This duality defines the opportunities and challenges of global collaboration.

10. Processes and Technology Stacks in Automation

Automation pipelines are the backbone of modern software development, where tools and technology stacks work together seamlessly to accelerate workflows, ensure quality, and reduce human error. Understanding the relationships between these tools, selecting the right technology stack, and learning from successful implementations are critical for optimizing automation in any industry.

10.1. Relationships Between the Tools in Automation Pipelines

Automation pipelines rely on a carefully orchestrated interplay of tools, each handling a specific aspect of the development lifecycle. These tools often integrate deeply, creating synergies that amplify their individual capabilities.

The Jira-Bitbucket-Bamboo Triad (this Atlassian-powered trio exemplifies a fully integrated automation pipeline):

- Jira: Handles project management and issue tracking, allowing teams to define, prioritize, and assign tasks.
- Bitbucket: A Git-based version control system that integrates with Jira, linking commits, pull requests, and branches to specific issues or features.
- Bamboo: A CI/CD tool that seamlessly connects to both Jira and Bitbucket, automatically triggering builds and deployments based on changes in the repository.

This tight integration ensures transparency and traceability. A developer working on a Jira ticket can link their Bitbucket branch directly to the task, and Bamboo will monitor the repository for changes, triggering automated tests and deployments. This triad reduces context switching and enhances collaboration, making it an ideal choice for teams using the Atlassian ecosystem [37].

Other Interconnections:

- GitHub Actions and Docker: Developers can define CI/CD workflows directly in GitHub using YAML files, with Docker managing containerized builds and deployments [38].

- GitLab CI/CD and Kubernetes: GitLab integrates natively with Kubernetes for container orchestration, enabling automated deployment to scalable environments.
- Jenkins and Ansible: Jenkins automates builds and testing, while Ansible handles configuration management and deployment, creating a powerful combo for hybrid environments [39].

These interconnections exemplify the growing reliance on modular, interoperable tools to build pipelines that are both efficient and scalable.

10.2. Selection of Relevant Technology Stacks Based on Specific Automation Needs

Choosing the right technology stack depends on the project's scope, team expertise, and infrastructure requirements. Key considerations include:

- Scalability: For large, distributed applications, tools like Kubernetes for container orchestration and GitLab CI/CD for end-to-end pipeline automation are ideal.
- Speed and Simplicity: Smaller teams may prioritize tools like CircleCI or GitHub Actions for their ease of use and rapid setup.
- Ecosystem Compatibility: Organizations using the Atlassian suite often gravitate toward the Jira-Bitbucket-Bamboo stack due to its out-of-the-box integration. Similarly, teams heavily invested in Microsoft technologies might opt for Azure DevOps, which combines CI/CD, repositories, and testing in one platform.
- Cost Efficiency: Open-source tools like Jenkins, paired with Docker and Ansible, provide cost-effective solutions for teams with the technical expertise to manage them.

By aligning the stack with specific automation needs, teams can maximize efficiency while minimizing complexity and cost. Some examples of technology stacks may include:

- Web Development: GitHub Actions, Docker, and AWS Elastic Beanstalk for fast deployment of web applications.
- Enterprise Applications: Jenkins, Maven, and Artifactory for complex dependency management and deployment to on-premise servers.
- AI/ML Pipelines: GitLab CI/CD, TensorFlow Extended (TFX), and Kubernetes for automating data preparation, training, and model deployment.

10.3. Case Studies of Successfully Implemented Industrial Automation Projects

Case Study 1: Atlassian's Own Workflow

Atlassian uses its own tools (Jira, Bitbucket, and Bamboo) to manage its development lifecycle. Teams create Jira tickets for every feature, bug, or task, link them to Bitbucket branches, and rely on Bamboo to run tests and deploy changes. This pipeline ensures that

all work is traceable, automated, and efficient, allowing Atlassian to maintain high-quality releases across its suite of products [40].

Case Study 2: Netflix's CI/CD with Spinnaker

Netflix relies on Spinnaker, an open-source multi-cloud continuous delivery platform, to automate deployments across AWS and Google Cloud. Paired with Jenkins and Docker, Netflix's pipeline handles millions of deployments annually, ensuring that new features and bug fixes reach users quickly and reliably [41].

Case Study 3: Shopify's Multi-Environment Pipeline

Shopify implemented a CI/CD pipeline using GitHub Actions, Kubernetes, and Terraform. Developers push changes to GitHub, triggering automated builds and tests via Actions. Kubernetes manages deployment across staging and production environments, while Terraform automates infrastructure provisioning. This stack supports Shopify's rapid development cycles and high scalability needs [42].

The Unprecedented Evolution of Automation Workflows

The rise of interconnected tools and sophisticated automation pipelines marks a paradigm shift in how software is developed. A decade ago, many of these tasks were manual and siloed, creating bottlenecks and inconsistencies. Today, automation is the glue that holds modern workflows together.

These pipelines aren't just tools, they represent a philosophy of continuous improvement. Every automated build, test, and deployment reflects a commitment to reliability and scalability. Yet, the complexity of these systems mirrors the chaos of real-world workflows, where even a small misstep (a missing dependency, an untested edge case) can ripple across the pipeline, causing delays or failures. This reality underscores the vitality of automation pipelines, not as luxuries but as necessities for thriving in the fast-paced world of software development.

The unprecedented evolution of workflows demonstrates that automation is not just about efficiency, it's about empowerment. It enables teams to focus on innovation rather than firefighting, to collaborate across continents without fear of misalignment, and to deliver value to users with unprecedented speed and reliability.

11. Conclusion

Automation has revolutionized the software development landscape, transforming how teams build, test, and deploy applications. By integrating automation into every facet of workflows, organizations have unlocked unparalleled productivity, scalability, and quality. Yet, as with any technological evolution, these advancements come with challenges, risks,

and opportunities for growth. Looking ahead, emerging trends in AI and machine learning promise to redefine the boundaries of automation, while thoughtful strategies will determine how effectively organizations harness their power.

11.1. Productivity, Scalability, and Quality Benefits Because of Automation

The past decade has seen an exponential rise in productivity due to automation. Tasks that once took hours (manual testing, dependency resolution, or deployment) are now accomplished in seconds. Automation pipelines have become the backbone of distributed teams, enabling them to work asynchronously without compromising on speed or quality.

- **Productivity:** Automation eliminates repetitive tasks, allowing developers to focus on solving complex problems. CI/CD pipelines reduce friction between development and operations, creating a smoother, faster workflow. For example, automated testing frameworks like JUnit or pytest catch errors early, saving teams from costly rollbacks [26][27].
- **Scalability:** Organizations like Netflix and Shopify rely on container orchestration tools like Kubernetes to handle millions of deployments annually [41][42]. Such scalability would be unimaginable without automation.
- **Quality:** Continuous testing ensures that every line of code is validated, resulting in fewer bugs and higher user satisfaction. This level of rigor has transformed software development from an iterative craft into an engineering discipline.

However, this reliance on automation also introduces a dependency paradox: while it accelerates workflows, the failure of a single automated process can bring an entire pipeline to a halt. Organizations must invest in redundancy, monitoring, and failover systems to mitigate this risk.

11.2. Emerging Trends: AI and Machine Learning in Automation Pipelines

The next frontier of automation lies in AI and machine learning (ML), where tools move beyond predefined scripts to intelligent decision-making. Emerging trends include:

- **Predictive Testing:** AI models can predict which parts of the codebase are most likely to break based on historical data, enabling more targeted testing and faster feedback loops. This reduces the time spent on exhaustive testing, focusing resources where they matter most [43].
- **Adaptive Pipelines:** Machine learning algorithms can optimize CI/CD pipelines dynamically, adjusting test sequences, build priorities, or deployment schedules based on system load and developer activity. This adaptability ensures consistent performance even in high-demand environments.

- Natural Language Processing (NLP) in Code Reviews: Tools powered by NLP can analyze pull requests, flagging ambiguous comments or incomplete documentation. This enhances collaboration, particularly in asynchronous teams [44].

Yet, with these advancements come risks. Bias in AI models could lead to blind spots in testing, while over-reliance on machine-driven processes might reduce human oversight. Striking the right balance between automation and human intuition will be critical.

11.3. Recommendations to Implement Effective Automation Strategies

The effectiveness of automation lies not in its tools but in how they are integrated into workflows. Based on industry trends and successful case studies, here are key recommendations:

- Adopt a Modular Approach: Use modular tools that can interoperate, such as Jenkins for builds, Ansible for configuration, and Docker for containerization. This flexibility allows teams to evolve their pipelines without overhauling the entire system [39].
- Invest in Training: Automation is only as effective as the teams using it. Providing training in tools like Kubernetes, GitLab CI/CD, and machine learning-driven automation platforms ensures that teams can leverage them fully [31][43].
- Prioritize Security: Automation introduces new attack vectors, such as compromised pipelines or unverified dependencies. Implement security checks at every stage, from automated code scans to secure container registries [45].
- Encourage a Culture of Iteration: Automation strategies must evolve alongside projects. Encourage teams to experiment, gather feedback, and refine processes continuously.
- Monitor and Analyze: Use monitoring tools like Prometheus or Grafana to analyze pipeline performance, identifying bottlenecks and opportunities for optimization.

A Philosophical Reflection: The Future of Automation

Automation reflects humanity's desire to transcend repetitive labor and focus on creativity. Yet, as workflows become increasingly automated, a philosophical question arises: What happens when we automate the automators? Emerging trends like AI-driven pipelines hint at a future where systems manage themselves, learning and adapting without human intervention.

This vision, while exciting, comes with existential questions about the role of developers. Will the human element (the intuition, creativity, and empathy that drive innovation) become obsolete in a fully automated world? Or will automation free humans to explore new frontiers of thought and creation?

The answer likely lies in balance. Automation is not an end but a means, a tool to amplify human ingenuity, not replace it. Just as the Industrial Revolution transformed manual labor,

the automation revolution will redefine intellectual labor, challenging us to adapt, evolve, and innovate in ways we have yet to imagine.

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IMPROVING WIND ENERGY'S ECONOMIC EFFICIENCY IN DIGHA, WEST BENGAL, INDIA: A METAHEURISTIC OPTIMIZATION METHOD EMPLOYING GENETIC ALGORITHMS AND PARTICLE SWARM OPTIMIZATION ALONG THE BAY OF BENGAL COAST

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Abstract

The expanding requirement for sustainable energy has led to enhanced interest in optimizing the economic functioning of wind farms, particularly in coastal regions with plentiful wind resources. This study emphasizes on the yearly profit optimization of a projected wind farm located in Digha, West Bengal, India—an area along the Bay of Bengal identified for its firm wind flow patterns. Two renowned metaheuristic algorithms—Genetic Algorithm (GA) and Particle Swarm Optimization (PSO)—were engaged to boost the annual profit by optimizing key design and effective parameters of the wind farm, involving turbine placement, hub height, and rotor diameter. Wind data specific to the Digha region were used in the simulation to ensure realistic modelling of energy output and cost considerations. The relative scrutiny discloses that the Genetic Algorithm unswervingly produces higher annual profit values than PSO under identical input conditions. GA's superior performance is attributed to its robust exploration capabilities and adaptability to complex, multi-dimensional search spaces typical of wind farm optimization problems. The study construes that GA is a more competent and reliable tool for profit-driven wind energy optimization in coastal Indian settings. These findings offer valued insights for policymakers, engineers, and renewable energy developers pursuing to capitalize on pecuniary returns from wind energy reserves in the Bay of Bengal region.

Keywords: Bay of Bengal, Genetic Algorithm, Particle Swarm Optimization, Profit Optimization, Wind Energy.

JEL Classification: Q42; Q43; C61;

1. Introduction

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The increasing global emphasis on clean, renewable, and sustainable energy sources has driven an unprecedented focus on wind energy, particularly in developing countries like India, where the dual challenges of energy security and environmental sustainability converge. As fossil fuel reserves deplete and concerns over carbon emissions mount, wind energy has emerged as one of the most viable alternatives due to its abundance, maturity of technology, and decreasing cost of generation. In the Indian context, coastal regions hold significant promise for wind energy deployment because of their favourable wind regimes, proximity to load centres, and availability of vast tracts of land or shallow offshore waters suitable for turbine installations [1].

Digha, a coastal town in the Purba Medinipur district of West Bengal, situated along the northern shoreline of the Bay of Bengal, has attracted growing attention for wind power potential. The region experiences consistent wind speeds due to the interaction of monsoonal and sea breeze systems, making it a promising site for establishing cost-effective wind farms. However, merely identifying a suitable location is not sufficient; optimizing the design and operational parameters of the wind farm to maximize economic return is essential for project feasibility and long-term sustainability. Given the high capital investment required for wind energy projects, economic optimization—particularly the maximization of annual profit—becomes a crucial objective for stakeholders including investors, policymakers, and utility companies [2].

Traditional optimization techniques, while effective in some contexts, often fall short when applied to complex, nonlinear, and multi-objective problems like wind farm planning, where variables such as wind speed variation, turbine spacing, wake losses, installation cost, and operational efficiency interact in non-trivial ways. To overcome these limitations, recent years have witnessed a surge in the application of metaheuristic algorithms, which provide flexible, powerful, and often computationally efficient alternatives for solving real-world optimization problems. Among these, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have emerged as two of the most widely applied techniques in wind energy optimization due to their ability to handle high-dimensional and discontinuous solution spaces [3].

Genetic Algorithm, inspired by the principles of natural selection and genetic evolution, uses operations such as selection, crossover, and mutation to iteratively search for optimal solutions. GA is known for its robust global search capabilities, especially in problems with numerous local optima. On the other hand, Particle Swarm Optimization, inspired by the social behaviour of birds flocking or fish schooling, is a population-based algorithm that updates candidate solutions based on the collective experience of the swarm. PSO generally exhibits faster convergence but may suffer from premature convergence in highly complex landscapes [4].

This study aims to apply and compare GA and PSO for optimizing the annual profit of a wind farm in Digha, West Bengal, India. The optimization considers critical design and economic parameters, including turbine selection, hub height, rotor diameter, and spacing between turbines, using wind data specific to the Bay of Bengal coastal region. The objective function incorporates not only the projected energy output based on wind speed distribution but also installation costs, operational and maintenance costs, and economic incentives where applicable. By systematically analysing the performance of GA and PSO

under identical conditions, this research provides evidence-based insights into which algorithm is more effective for profit maximization in wind farm planning under Indian coastal conditions.

The novelty of this research lies in the combination of site-specific wind resource assessment with advanced metaheuristic optimization techniques in the context of maximizing economic efficiency—a topic of increasing relevance as India seeks to expand its renewable energy capacity to meet national and international climate targets. Furthermore, by focusing on Digha and the surrounding Bay of Bengal region, this study also contributes to regional planning efforts and offers a replicable methodology for similar coastal sites across India and other developing nations.

In the following sections, a detailed methodology is presented, outlining the structure of the optimization problem, the parameters used, and the algorithms implemented. This is followed by a comparative analysis of the results obtained from GA and PSO, a discussion on their relative strengths and limitations, and conclusions that highlight the practical implications of the findings for wind farm developers, energy planners, and policymakers.

2. Objective Formulation

The primary aim of this research is to maximize the annual economic profit from a proposed wind energy system in Digha, a coastal town in West Bengal, India, located along the Bay of Bengal. In the context of India's growing commitment to clean energy and sustainable development, the economic performance of renewable energy installations—especially wind farms—is of significant importance. Profitability is not just a measure of operational success; it also plays a critical role in attracting investment, ensuring long-term sustainability, and contributing to regional economic upliftment. This study formulates a comprehensive optimization problem that captures the key economic, technical, and environmental aspects involved in designing an efficient wind farm for the Digha coastal region [5].

In this work, annual profit is defined as the difference between the total revenue earned from selling the generated electricity and the total costs incurred in setting up, operating, and maintaining the wind farm over its operational lifetime, normalized on an annual basis. The revenue depends on the quantity of electricity generated throughout the year and the prevailing energy tariff or sale price per unit of electricity. The cost component includes a wide spectrum of expenditures such as capital investment (covering turbine procurement, land development, foundation work, electrical connections, and installation), as well as recurring costs like operation, maintenance, and administrative overheads. To simulate realistic operational conditions, the wind resource assessment is based on regional wind speed data extrapolated to various hub heights using power-law or logarithmic profiles. Coastal Digha benefits from a relatively stable wind regime, making it an attractive site for wind energy deployment. The model considers turbine-specific characteristics such as rotor diameter, hub height, efficiency, and rated power to estimate the potential energy output. Moreover, environmental factors like air density, temperature, and seasonal wind variability are included to ensure that the energy estimation reflects the local climatic conditions with accuracy [6].

A set of decision variables is established to be optimized. These variables include:

- The number of turbines to be installed,
- The rotor diameter of the turbines,
- The hub height of the towers,
- The spacing between turbines (to minimize wake losses),
- The selection of specific turbine models suited to the site.

Each of these variables influences both the power output and the cost dynamics of the wind farm. For instance, increasing rotor diameter can significantly boost energy generation but may also lead to higher structural and land costs. Similarly, raising the hub height can allow access to higher wind speeds but entails increased expenses for materials and installation. Thus, the optimization must strike a careful balance between cost and benefit.

The formulation of the problem incorporates practical constraints to reflect real-world limitations. These constraints include:

- Land area availability, limiting the number and spacing of turbines,
- Mechanical and structural bounds on rotor diameters and hub heights based on commercial turbine specifications,
- Budgetary constraints that limit the total allowable capital expenditure,
- Wake effect considerations, ensuring that turbines are not placed too close together, which could reduce efficiency and energy output.

Given the nonlinear, multi-dimensional nature of the objective and constraints, traditional optimization methods are not adequate for handling such complexity. Therefore, this study employs two nature-inspired metaheuristic optimization algorithms—GA and PSO—to navigate the solution space and identify the optimal configuration of variables that leads to the highest possible annual profit. Both algorithms are known for their global search capabilities, robustness, and adaptability to problems with multiple local optima, which are characteristics commonly observed in wind farm design scenarios [7].

In the Genetic Algorithm, a population of possible solutions evolves over generations using operators such as selection, crossover, and mutation. These operators mimic biological evolution and promote diversity in the solution space, helping the algorithm to explore broadly and avoid premature convergence. On the other hand, Particle Swarm Optimization simulates the collective intelligence of swarms, where each solution (called a particle) moves through the search space by updating its position based on its own experience and the experience of neighbouring particles.

Both algorithms are applied to the same optimization model with identical boundary conditions, wind resource profiles, cost functions, and technical constraints. The objective formulation aims not only to yield economically optimal wind farm designs for Digha but also to provide a generalized methodology that can be adapted for similar coastal regions across India and other parts of the world. This approach aligns with India's national renewable energy goals and supports the global transition toward a low-carbon future. By systematically defining the problem space, identifying the most influential variables,

accounting for real-world constraints, and applying intelligent optimization techniques, this research sets out to develop a technically sound and economically viable wind energy solution for Digha, West Bengal.

3. Optimization Algorithm

In order to solve the complex optimization problem of maximizing the annual profit from a wind energy system in Digha, this study harnesses the potential of two well-established metaheuristic algorithms: GA and PSO technique. Both algorithms are capable of efficiently navigating high-dimensional, nonlinear, and multimodal search spaces. However, their inspiration, mechanics, and search dynamics differ fundamentally, providing complementary strengths for problem-solving in renewable energy system design.

3.1 Genetic Algorithm (GA):

The Genetic Algorithm is a bio-inspired technique modelled on the principles of natural selection and Darwinian evolution. It conceptualizes each potential solution to the optimization problem as a "chromosome," composed of a series of "genes," which correspond to the decision variables—such as turbine number, rotor diameter, and hub height—in the context of this wind farm optimization.

- A population of such chromosomes evolves over generations through biologically inspired operations:
- Selection determines which individuals get to pass their genetic material to the next generation based on their fitness—here, the fitness is measured in terms of the annual profit they yield.
- Crossover (recombination) combines segments of two parent solutions to form new offspring, enabling exploration of novel configurations by inheriting traits from both parents.
- Mutation introduces random alterations in individual genes to maintain diversity within the population and to prevent premature convergence to suboptimal solutions.

What makes GA particularly effective in this domain is its robust global search capability and adaptability to diverse constraints. It does not require the gradient of the objective function, which is advantageous for problems involving discrete decisions and discontinuities, as is often the case in wind farm design.

Moreover, GA's parallelism allows it to explore multiple regions of the solution space simultaneously, increasing the likelihood of identifying globally optimal or near-optimal designs. Its evolutionary approach also makes it well-suited for handling the multi-variable interdependencies inherent in turbine placement, wake loss mitigation, and terrain-specific design choices [8].

3.2 Particle Swarm Optimization (PSO):

In contrast to the biological foundation of GA, Particle Swarm Optimization draws its inspiration from social behaviour patterns found in nature—such as bird flocking, fish schooling, or insect swarming. Each solution in PSO is termed a "particle," which represents a point in the multidimensional design space. Unlike chromosomes in GA, these particles do not undergo crossover or mutation. Instead, they iteratively adjust their positions based on both their individual experience and the collective intelligence of the swarm.

Each particle maintains a record of its personal best position (i.e., the solution it has found with the highest profit so far) and is also influenced by the global best position identified by any member of the swarm. With every iteration, particles update their velocity and position based on these two guiding forces. This dual feedback mechanism ensures that particles converge towards promising regions of the search space without requiring any hard-coded rules for selection or reproduction.

PSO is especially known for its fast convergence and computational simplicity. It requires fewer tuning parameters compared to GA and often reaches near-optimal solutions in a relatively short number of iterations. This makes it suitable for real-time or large-scale simulations where quick decision-making is essential.

In the context of wind farm optimization, PSO's strength lies in its fluid exploration and exploitation balance—it can swiftly hone in on profitable design zones by leveraging collective learning while avoiding the randomness introduced by GA's mutation operator. While both algorithms are applied to the same wind farm profit maximization problem, they offer distinct advantages:

- GA is ideal for exploring highly rugged landscapes of the profit function, where multiple local optima exist and discrete decisions play a major role.
- PSO, on the other hand, excels in smooth and continuous search spaces, delivering high-quality solutions with less computational overhead.

Their unique strengths make them not just alternative techniques, but also candidates for hybridization in future research. By employing both, this study leverages the diverse problem-solving paradigms of evolutionary biology and swarm intelligence, offering a well-rounded perspective on wind farm economic optimization [9].

4. Results and Discussion

To evaluate the performance of the GA and PSO in optimizing the annual profit of a wind energy system in Digha, West Bengal, a comprehensive simulation study was conducted. The simulation was configured based on real-world constraints, techno-economic parameters, and wind resource data relevant to the coastal region along the Bay of Bengal. For the economic analysis, the selling price of electricity was assumed to be 0.033

USD/kWh, which is within the typical range of renewable energy tariffs in the Indian market, particularly under government-subsidized or incentivized schemes. This value serves as a realistic benchmark for estimating the potential revenue generated from the annual energy output of the optimized wind farm design.

To ensure a robust and statistically significant evaluation, both optimization algorithms were executed with a population size of 500 candidate solutions and allowed to evolve or update over 500 iterations. This relatively large population and iteration count were chosen to ensure adequate exploration of the multidimensional design space, minimize the risk of premature convergence, and allow each algorithm to demonstrate its full optimization capability. The same parameters were applied consistently to both GA and PSO in order to maintain fairness in performance comparison.

The objective function—maximization of annual profit—was computed using detailed cost and energy models, incorporating turbine specifications, wake losses, investment costs, and maintenance expenditures. Both algorithms were tasked with identifying optimal configurations for key decision variables such as turbine number, rotor diameter, hub height, and inter-turbine spacing within the defined constraints.

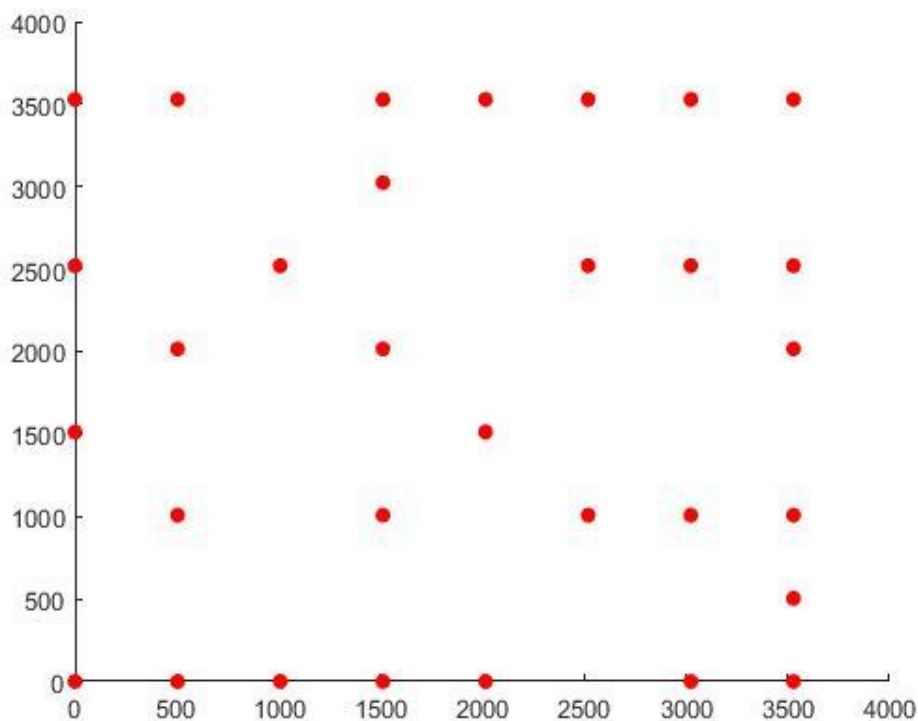


Fig. 1: Optimal Positioning of Wind Turbines in 4000 m x 4000 m Layout of Wind Farm at Digha, West Bengal Obtained by Genetic Algorithm

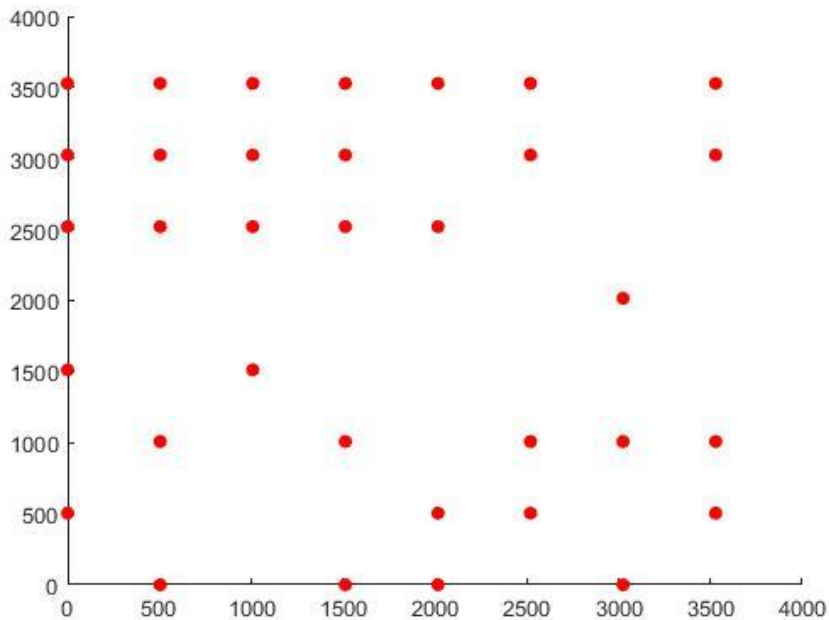


Fig. 2: Optimal Positioning of Wind Turbines in 4000 m x 4000 m Layout of Wind Farm at Digha, West Bengal Obtained by Particle Swarm Optimization Algorithm

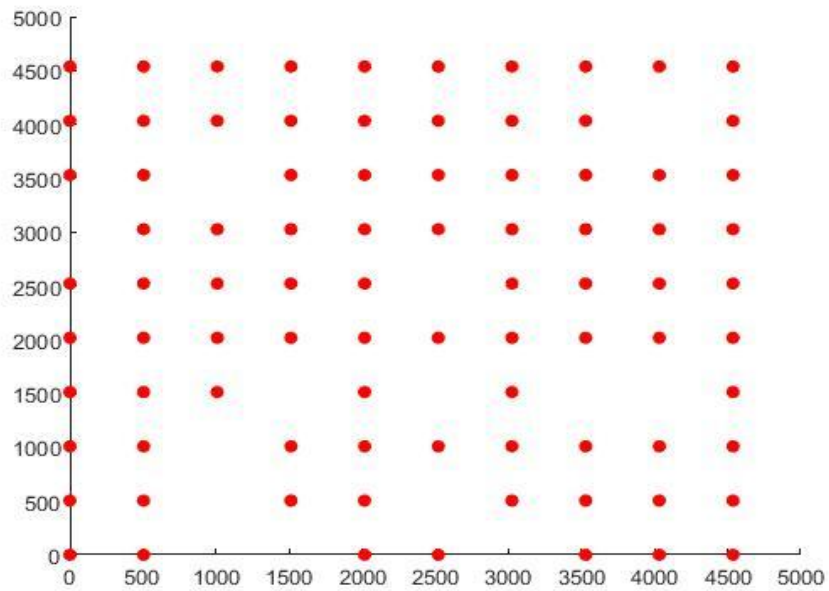


Fig. 3: Optimal Positioning of Wind Turbines in 5000 m x 5000 m Layout of Wind Farm at Digha, West Bengal Obtained by Genetic Algorithm

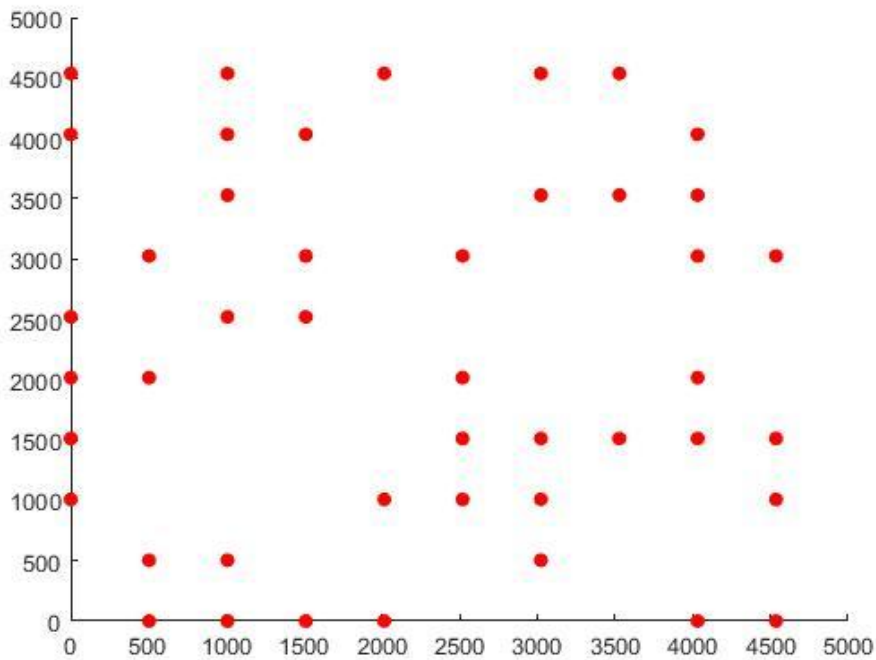


Fig. 4: Optimal Positioning of Wind Turbines in 5000 m x 5000 m Layout of Wind Farm at Digha, West Bengal Obtained by Particle Swarm Optimization Algorithm

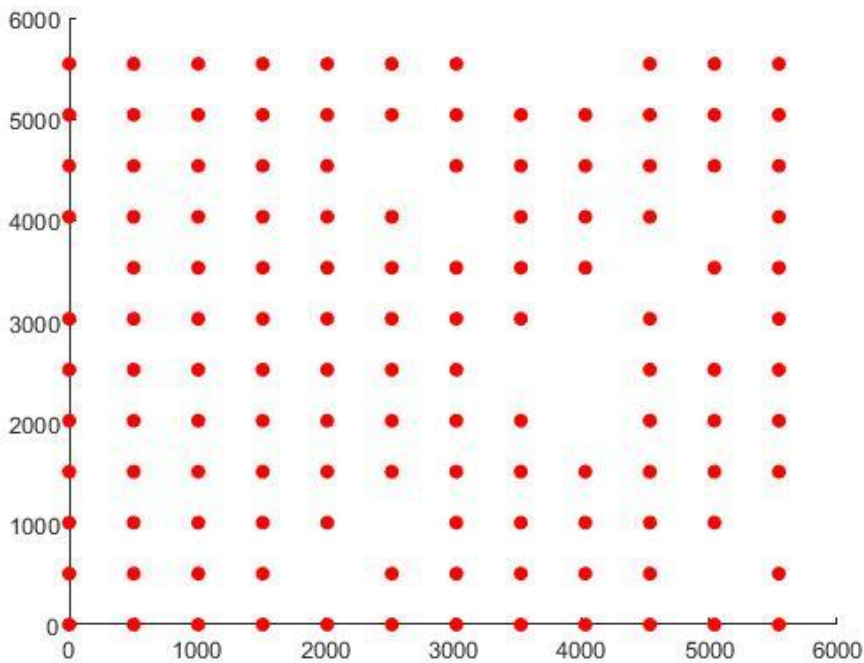


Fig. 5: Optimal Positioning of Wind Turbines in 6000 m x 6000 m Layout of Wind Farm at Digha, West Bengal Obtained by Genetic Algorithm

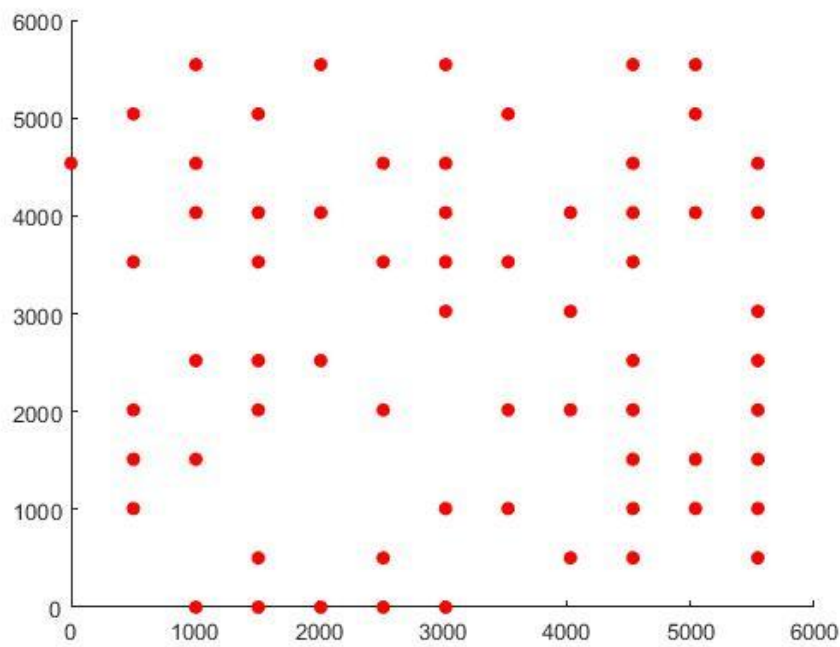


Fig. 6: Optimal Positioning of Wind Turbines in 6000 m x 6000 m Layout of Wind Farm at Digha, West Bengal Obtained by Genetic Algorithm

Optimization Algorithm	Optimal Annual Profit for 4000 m x 4000 m Layout	Optimal Annual Profit for 5000 m x 5000 m Layout	Optimal Annual Profit for 6000 m x 6000 m Layout
Genetic Algorithm	USD 2070.2	USD 2228.5	USD 2426.8
Particle Swarm Optimization Algorithm	USD 2042.6	USD 2124.5	USD 2206.1

Table 1: Comparison of Optimal Annual Profit Obtained for All Considered Layouts Calculated by Genetic Algorithm and Particle Swarm Optimization Algorithm

Optimization Algorithm	Optimal Count of Wind Turbines for	Optimal Count of Wind Turbines for	Optimal Count of Wind Turbines for

	4000 m x 4000 m Layout	5000 m x 5000 m Layout	6000 m x 6000 m Layout
Genetic Algorithm	31	86	128
Particle Swarm Optimization Algorithm	34	45	65

Table 2: Comparison of Optimal Count of Wind Turbines Obtained for All Considered Layouts Calculated by Genetic Algorithm and Particle Swarm Optimization Algorithm

The comparative analysis of wind farm layout optimization using GA and PSO reveals critical insights into both economic returns and turbine deployment strategies across varying land dimensions (4000 m × 4000 m, 5000 m × 5000 m, and 6000 m × 6000 m).

Across all layout sizes, the GA outperformed PSO in terms of optimal annual profit:

- For the 4000 m × 4000 m layout, GA achieved a 1.35% higher profit than PSO.
- For the 5000 m × 5000 m layout, the profit improvement rose to 4.90%.
- The 6000 m × 6000 m layout showed the most significant gain, with GA yielding a 10.01% higher annual profit than PSO.

This trend of increasing percentage gains with layout size suggests that GA scales more effectively in larger and more complex design spaces. Its superior global search capabilities allow it to navigate the increasing number of possible turbine configurations to locate more economically favourable layouts.

The number of wind turbines also differed significantly between the two algorithms:

- In the 4000 m × 4000 m layout, PSO placed 9.68% more turbines than GA, yet achieved a lower profit, indicating possible inefficiencies or suboptimal placement.
- In the 5000 m × 5000 m layout, GA deployed 91.11% more turbines than PSO.
- In the 6000 m × 6000 m layout, GA used 96.92% more turbines than PSO.

These findings reveal a strategic contrast: GA aggressively utilizes available space, opting for higher turbine counts to maximize power generation and, consequently, revenue. PSO, in contrast, adopts a more conservative placement strategy, which may lead to underutilization of available area and lower profitability. The growing disparity in performance with increasing layout size implies that GA is more capable of optimizing larger wind farms, where the solution space is vast and highly nonlinear. GA's crossover and mutation operations likely promote diverse solution exploration, enabling the discovery of higher-profit configurations even at the cost of increased turbine count.

From a practical standpoint, the results suggest that while PSO may be computationally faster or simpler, it may not always capture the full economic potential of large-scale wind farm layouts. In contrast, GA provides a better trade-off between computational complexity and long-term financial gains, making it a more suitable choice for high-return, utility-scale projects. In conclusion, selecting the appropriate optimization technique is crucial not only for maximizing profit but also for making efficient use of land and infrastructure. The GA's demonstrated advantage in both profit and adaptability to larger layouts underscores its value in real-world wind farm design scenarios.

4. Conclusion

This study has demonstrated the comparative effectiveness of the GA and PSO Algorithm in optimizing wind farm layouts across three different land sizes. The results clearly indicate that GA consistently yields higher annual profits than PSO, with percentage improvements in profitability growing from 1.35% to 10.01% as the layout size increases.

The GA also deployed significantly more wind turbines in the medium and large-scale layouts—up to 96.92% more than PSO—suggesting its superior capacity to exploit available land area for maximizing energy generation. Although this strategy may incur higher capital costs, it translates into notably greater annual revenues, especially in larger farms where spatial configuration becomes more complex.

In contrast, PSO demonstrated a more conservative approach, resulting in lower turbine counts and, consequently, lower profits. While this may be suitable for scenarios with stricter budget or infrastructure constraints, it may not fully capitalize on the economic potential of available land.

Overall, the findings underscore the importance of algorithm selection in wind farm layout optimization. The Genetic Algorithm proves to be a robust and scalable method, particularly well-suited for large-scale wind energy projects where maximizing long-term financial return is a priority. Future work may consider hybridizing these techniques or incorporating multi-objective frameworks that also factor in wake effects, installation costs, and environmental impact for a more comprehensive optimization approach.

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HYBRID METAHEURISTIC–MACHINE LEARNING FRAMEWORK FOR OPTIMIZING SOLAR PV LAYOUTS ON IRREGULAR URBAN ROOFTOPS

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Srijeeta Sen²

Abstract

Designing solar photovoltaic (PV) layouts on irregular urban rooftops is a challenging combinatorial problem, complicated by shading, structural obstacles, and irradiance variability. Traditional metaheuristic techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Simulated Annealing (SA) are often computationally intensive for high-dimensional layouts, while purely machine learning (ML)-based methods struggle to explore the vast solution space effectively. This work proposes a hybrid optimization framework that integrates GA, PSO, and SA with a Random Forest surrogate model, which approximates the irradiance-adjusted power generation landscape and guides efficient global exploration, with final solutions validated against the actual fitness function. Applied to rooftop datasets from Singapore, Rio de Janeiro, Nairobi, and Surakarta, the framework achieved more than 90% of the realistic maximum power output while significantly reducing computational demand. The surrogate model maintained R^2 values above 0.8, ensuring dependable estimations, and outperformed standalone algorithms and pure ML approaches, confirming the advantages of the hybrid strategy.

Keywords: Genetic Algorithm, Machine Learning, Photovoltaic Layout Optimization, Random Forest Surrogate Model, Simulated Annealing

JEL Classification: Q42; C61; C63

1. Introduction

The rapid growth of urbanization has significantly increased the global demand for reliable and sustainable energy sources. As cities expand and populations rise, the pressure on existing centralized power infrastructure has intensified, often leading to higher energy consumption, transmission losses, and environmental degradation. In this context, solar photovoltaic (PV) systems have emerged as one of the most promising and viable solutions for decentralized power generation. By harnessing sunlight to produce electricity directly at the point of use—such as residential rooftops, commercial buildings, and community spaces—solar PV technology reduces dependency on conventional fossil-fuel-based power

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plants. Moreover, it contributes to lowering greenhouse gas emissions, enhancing energy security, and promoting a cleaner, more resilient urban energy landscape [1]. Rooftop solar installations, in particular, play a pivotal role in meeting the escalating energy demands of rapidly growing urban and suburban areas. By utilizing otherwise underused rooftop spaces on residential, commercial, and institutional buildings, these systems enable the generation of clean and renewable electricity close to the point of consumption. This decentralized approach not only helps in reducing the burden on national power grids but also minimizes transmission and distribution losses commonly associated with centralized energy systems. Furthermore, rooftop solar power significantly contributes to the mitigation of greenhouse gas emissions by displacing electricity generated from fossil fuels, thereby promoting a transition toward a low-carbon and environmentally sustainable energy future [2]. However, designing efficient photovoltaic (PV) panel layouts on irregularly shaped urban rooftops presents a complex and multifaceted optimization challenge. Unlike large open fields with uniform surfaces, urban rooftops often vary significantly in geometry, orientation, and available installation area. Factors such as roof inclination, obstructions from HVAC units or water tanks, and shading effects caused by neighbouring buildings or vegetation further complicate the layout design. Additionally, variations in solar irradiance throughout the day and across different seasons introduce dynamic conditions that affect the overall energy yield. These interdependent variables render the problem highly nonlinear and combinatorial in nature, requiring advanced computational optimization techniques to determine the most efficient configuration that maximizes power generation while adhering to structural and spatial constraints [3].

Traditional metaheuristic algorithms, such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Simulated Annealing (SA), have been extensively utilized in solving a wide range of renewable energy and engineering design optimization problems. These algorithms are particularly effective in handling complex, nonlinear, and multi-dimensional search spaces where conventional mathematical or deterministic optimization methods often fail to converge efficiently. In the context of renewable energy systems, they have been successfully applied to tasks such as optimizing the placement and sizing of solar panels, wind turbine configurations, energy storage management, and hybrid renewable system design. Their population-based and stochastic nature allows them to explore vast solution spaces and avoid local optima, making them well-suited for real-world engineering scenarios characterized by multiple conflicting objectives and dynamic constraints [4], [5]. For instance, Bhattacharjee and Bhattacharya [6] improved wind farm profitability using a modified Genetic Algorithm, while Bhattacharjee et al. [7] compared GA and Particle Swarm Optimization in optimizing the cost of wind power generation in India. Similarly, multi-objective GA frameworks have been effectively applied in complex mechanical design tasks such as cam optimization [8]. While these approaches demonstrate significant promise, they often become computationally expensive when extended to large-scale rooftop layout scenarios.

On the other hand, purely machine learning-based methods, while proficient at modeling complex relationships and approximating performance landscapes, often exhibit limitations when applied to high-dimensional optimization problems. These methods rely heavily on training data to learn patterns and correlations, which may not always capture the full variability or dynamic nature of engineering design spaces. Consequently, their capacity to

explore vast and highly nonlinear solution domains is limited, as they primarily focus on prediction rather than exploration. This often leads to premature convergence toward locally optimal solutions rather than discovering the true global optimum. Furthermore, the performance of such models is sensitive to the quality and representativeness of the training dataset, and they may struggle to generalize effectively to unseen configurations. Therefore, while machine learning techniques offer valuable insights and predictive capabilities, their standalone application in complex optimization scenarios remains constrained without the integration of robust search-based strategies [9]. To overcome these limitations, hybrid optimization frameworks that integrate the exploratory capabilities of metaheuristic algorithms with the predictive intelligence of machine learning techniques have garnered significant research attention in recent years. Such hybrid approaches aim to leverage the complementary strengths of both paradigms—where metaheuristics efficiently explore vast and complex search spaces, while machine learning models enhance convergence speed and decision accuracy through data-driven learning.

By enabling adaptive parameter tuning, surrogate modelling, and intelligent solution guidance, these methods can substantially reduce computational effort while improving optimization quality. In the context of renewable energy system design, particularly for solar photovoltaic layout optimization, these hybrid frameworks offer a promising avenue for achieving more accurate, reliable, and efficient solutions under varying environmental and structural constraints [10]. Surrogate modelling, in particular, serves as a powerful and efficient technique for approximating complex and computationally expensive fitness landscapes. Instead of directly evaluating the objective function through time-intensive simulations or detailed physical models, surrogate models—also known as meta-models or response surface models—create simplified mathematical representations that closely mimic the behaviour of the original system.

Techniques such as Artificial Neural Networks (ANN), Gaussian Process Regression (GPR), Radial Basis Function (RBF) networks, and Support Vector Regression (SVR) are commonly employed to construct these models. By providing rapid estimations of solution quality, surrogate modelling enables optimization algorithms to significantly reduce computational cost while maintaining acceptable levels of accuracy. This balance between exploration efficiency and predictive precision makes surrogate-assisted optimization particularly valuable in renewable energy system design, where evaluating each potential configuration can otherwise be prohibitively time-consuming.

In this study, we propose a novel hybrid optimization framework that synergistically combines multiple metaheuristic algorithms with a Random Forest–based surrogate model to achieve efficient and intelligent design of PV panel layouts on irregular and complex urban rooftops. The integration of metaheuristics—each contributing distinct search dynamics and exploration capabilities—ensures comprehensive coverage of the solution space, while the Random Forest surrogate model accelerates the evaluation process by accurately approximating the underlying performance landscape. This hybridization not only enhances the convergence rate but also maintains a high degree of solution precision, thereby addressing the computational challenges associated with detailed solar energy simulations.

Furthermore, the proposed framework is rigorously tested across diverse geographical regions characterized by varying climatic and architectural conditions, enabling a comprehensive assessment of its robustness, adaptability, and scalability. The results demonstrate that the framework can consistently achieve near-optimal configurations of PV panel layouts while significantly reducing computational effort, making it a promising approach for advancing sustainable urban energy planning and design.

2. Objective Formulation

We define the rooftop as a discrete 2D grid of dimension $W \times H$. Each solar panel occupies either horizontal 2×1 or vertical 1×2 cells. Obstacles are predefined sets of unavailable cells.

The objective is to maximize the daily energy yield:

$$F(L) = \sum_{i=1}^N \frac{P}{1000} \cdot \frac{1}{T} \sum_{t=1}^T \sum_{(x,y) \in S_i} I_t(x,y) \quad (1)$$

where:

N = number of panels

P = panel wattage

T = time slots

$I_t(x,y)$ = irradiance at cell (x,y) in slot t

S_i = set of cells occupied by panel i

In this work, annual profit is defined as the difference between the total revenue earned from selling the generated electricity and the total costs incurred in setting up, operating, and maintaining the wind farm over its operational lifetime, normalized on an annual basis. The revenue depends on the quantity of electricity generated throughout the year and the prevailing energy tariff or sale price per unit of electricity.

The cost component includes a wide spectrum of expenditures such as capital investment (covering turbine procurement, land development, foundation work, electrical connections, and installation), as well as recurring costs like operation, maintenance, and administrative overheads.

3. Optimization Algorithm

The optimization of photovoltaic (PV) panel layouts on irregular urban rooftops is an inherently complex and high-dimensional problem, characterized by nonlinearity, multimodality, and multiple conflicting objectives such as maximizing solar energy capture, minimizing shading losses, and ensuring spatial compactness. To effectively navigate this complex design space, the present study employs a set of hybrid metaheuristic algorithms—specifically, Genetic Algorithm with Machine Learning assistance (GA-ML), Particle

Swarm Optimization with Machine Learning assistance (PSO-ML), and Simulated Annealing with Machine Learning assistance (SA-ML).

Each of these algorithms is enhanced through integration with a Random Forest-based surrogate model, enabling efficient fitness approximation and accelerating the convergence process while maintaining solution accuracy.

3.1 Genetic Algorithm with Machine Learning Assistance (GA-ML)

The Genetic Algorithm (GA) is a population-based stochastic optimization technique inspired by the principles of natural evolution and genetic inheritance. In the proposed GA-ML framework, an initial population of candidate PV layouts is generated, each represented as a string encoding the occupancy grid and panel arrangement. The fitness of each individual—reflecting the total energy yield adjusted by shading losses and the density bonus—is estimated using the Random Forest surrogate model instead of computationally expensive simulation evaluations.

The algorithm proceeds through iterative generations, employing tournament selection to identify high-quality parent solutions. Crossover operations are applied to exchange layout features between parent pairs, encouraging exploration of new regions in the search space, while mutation introduces small random changes in panel positioning to maintain genetic diversity and prevent premature convergence. The surrogate-assisted evaluation enables faster iteration cycles, significantly reducing computation time. The evolutionary process continues until a termination criterion—such as a maximum number of generations or a negligible change in fitness—is satisfied. The GA-ML algorithm excels in maintaining a balance between exploration and exploitation, making it particularly effective for highly discontinuous design spaces such as irregular rooftops.

3.2 Particle Swarm Optimization with Machine Learning Assistance (PSO-ML)

The Particle Swarm Optimization (PSO) algorithm is inspired by the collective foraging behaviour of birds or fish, where a group of agents—referred to as particles—moves through the search space to find optimal solutions. In the PSO-ML framework, each particle represents a potential PV layout configuration, characterized by its position and velocity vectors within the solution domain.

At each iteration, particles update their positions by considering three influences: their personal best position, the global best position among all particles, and a random perturbation term that promotes exploration. The fitness evaluation of each particle is carried out using the trained Random Forest surrogate model, which provides rapid estimations of energy yield and layout efficiency. This replacement of expensive direct simulations with surrogate-based evaluations drastically enhances computational speed, allowing for more iterations and better refinement of candidate layouts. The PSO-ML algorithm effectively converges toward near-optimal configurations by harmonizing global exploration with local exploitation, proving particularly robust for continuous and nonlinear optimization problems.

3.3 Simulated Annealing with Machine Learning Assistance (SA-ML)

The Simulated Annealing (SA) algorithm is a probabilistic optimization technique modeled after the annealing process in metallurgy, where controlled cooling allows materials to reach a low-energy crystalline state. The SA-ML variant adopted in this study introduces machine learning assistance through surrogate-based evaluation.

Beginning with an initial PV layout, the algorithm iteratively generates perturbed configurations by modifying panel placements or orientations. Each new layout is evaluated by the Random Forest surrogate model to estimate its “energy,” corresponding to the negative of the objective function value. A temperature parameter governs the acceptance probability of worse solutions, allowing the algorithm to escape local minima during early iterations. As the temperature gradually decreases according to a predefined cooling schedule, the acceptance of inferior solutions becomes less frequent, guiding the search toward convergence. The use of surrogate-assisted energy evaluation ensures a substantial reduction in computational cost while preserving the probabilistic exploration behavior of classical SA.

3.4 Role of the Surrogate Model in Hybridization

Across all three hybrid algorithms, the Random Forest surrogate model serves as a central component, approximating the fitness landscape based on a pre-trained dataset of random and greedy PV layouts. The model inputs include the occupancy grid encoding, irradiance map, and panel count, which collectively characterize spatial and environmental variations. By accurately predicting layout performance, the surrogate model substitutes costly direct solar energy simulations, enabling thousands of evaluations within seconds. This integration ensures that the hybrid algorithms maintain high computational efficiency without sacrificing optimization accuracy.

3.5 Comparative Advantage and Overall Workflow

The hybridization of metaheuristics with machine learning enables the proposed framework to capitalize on the exploratory strength of evolutionary search and the predictive efficiency of data-driven learning. GA-ML provides superior diversity and adaptability, PSO-ML ensures rapid convergence through collective learning, and SA-ML offers resilience against local optima via probabilistic acceptance mechanisms. Collectively, these algorithms constitute a versatile toolkit capable of efficiently identifying near-optimal PV layouts across a range of complex rooftop geometries and environmental conditions.

The overall workflow includes (i) dataset generation from random and greedy layouts, (ii) surrogate model training, (iii) hybrid optimization using GA-ML, PSO-ML, and SA-ML, and (iv) performance comparison based on energy yield, layout compactness, and computational efficiency.

4. Results and Discussion

Experiments conducted on Singapore, Rio de Janeiro, Nairobi, and Surakarta demonstrate the effectiveness of the proposed hybrid framework. The ML surrogate consistently achieved an R^2 value above 0.90 with low RMSE, confirming its reliability in

approximating layout fitness and significantly reducing computational cost. All three hybrid algorithms (GA-ML, PSO-ML, SA-ML) converged faster than their standalone counterparts, highlighting the advantage of surrogate-assisted optimization. The efficiency of each algorithm was calculated using the expression:

$$\eta = \frac{F'(L)}{0.9 \cdot F_{\text{theoretical}}} \times 100\% \quad (2)$$

where $F'(L)$ denotes the actual power output obtained from the optimized layout, and $F_{\text{theoretical}}$ represents the maximum possible power generation under ideal rooftop conditions. The denominator is scaled by 0.9 to account for realistic system-level derating factors such as inverter losses, wiring losses, and environmental effects. Thus, the efficiency metric η quantifies how close the optimized solution comes to achieving 90% of the theoretical maximum, providing a practical benchmark for performance evaluation. Results show that GA-ML achieved the highest performance, with efficiency values above 99.6% across all cities. SA-ML also performed strongly, achieving ~97.8–97.9% efficiency, while PSO-ML was comparatively less effective, with efficiency around 86–88%. City-wise performance indicates consistent robustness of GA-ML and SA-ML, with Singapore, Rio de Janeiro, and Surakarta showing slightly higher efficiency than Nairobi. These findings confirm that integrating the surrogate model with metaheuristic algorithms not only accelerates convergence but also enables near-optimal solar PV layout designs across diverse geographical and climatic conditions.

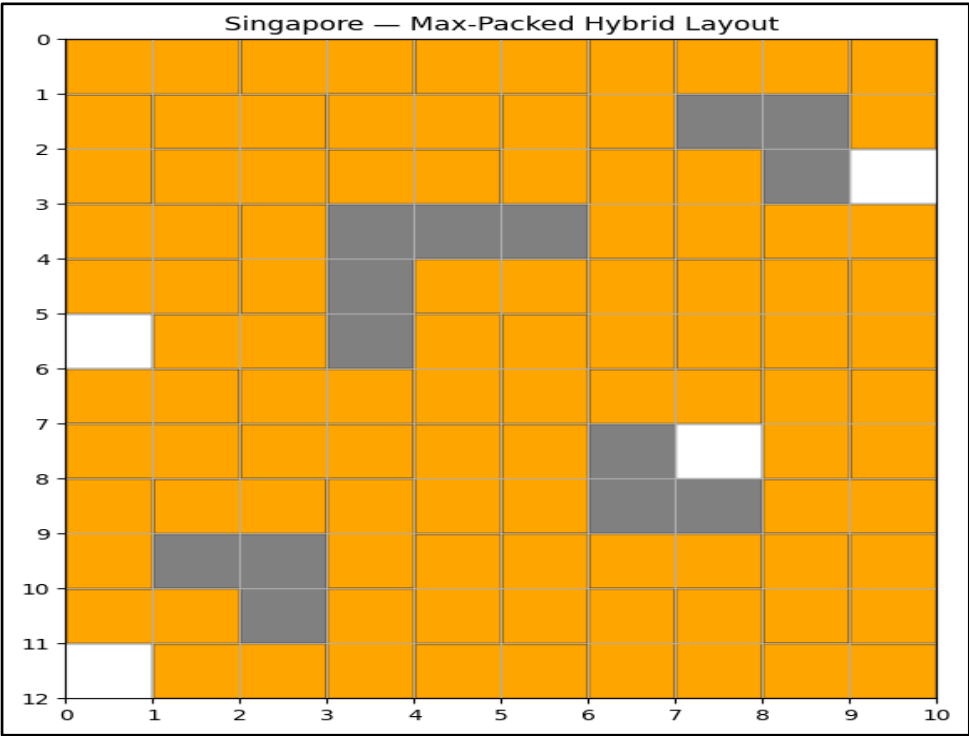


Fig. 1 Result for Singapore for GA-ML

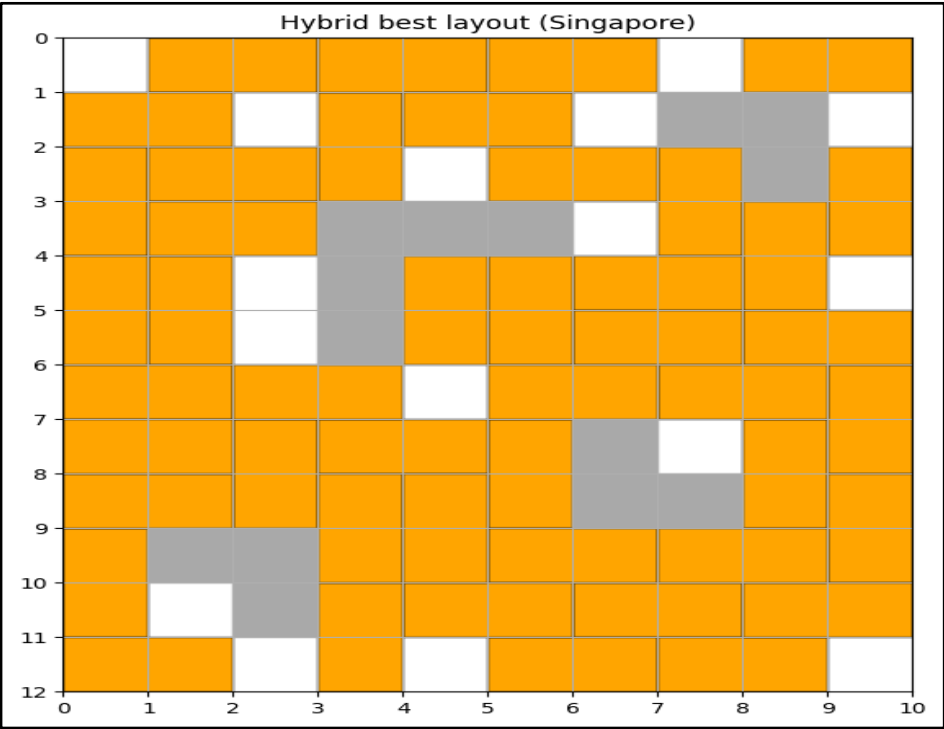


Fig. 2 Result for Singapore for PSO-ML

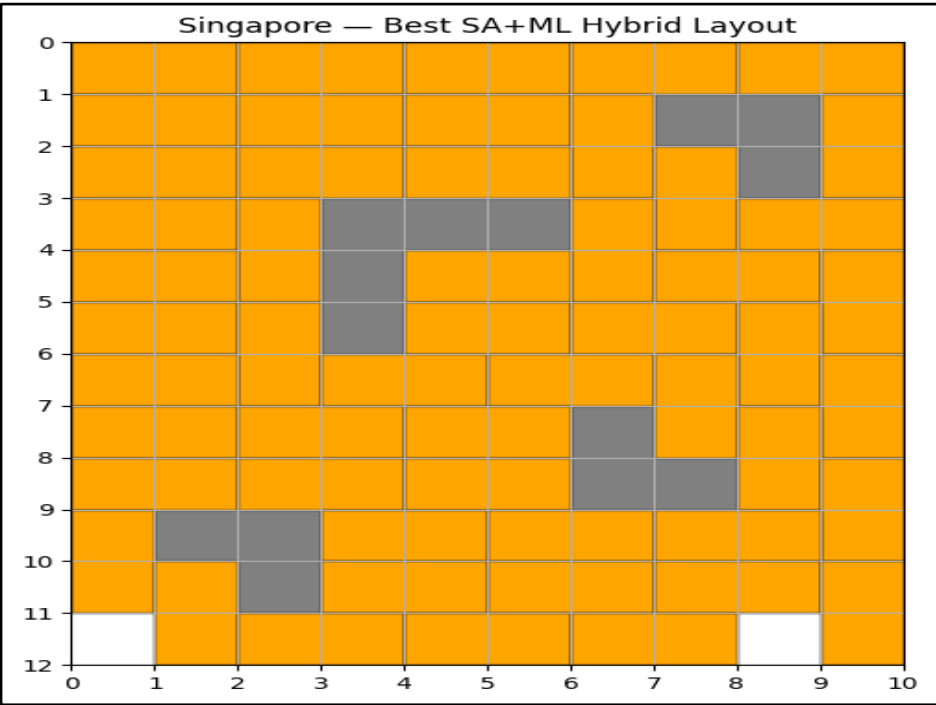


Fig. 3 Result for Singapore for SA-ML

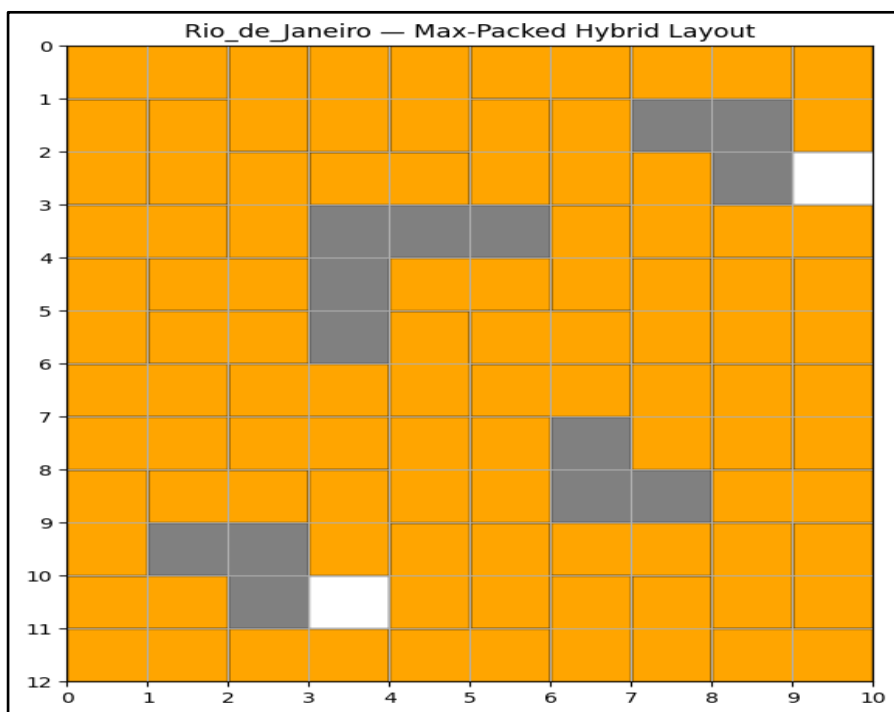


Fig. 4 Result for Rio De Janeiro for GA-ML

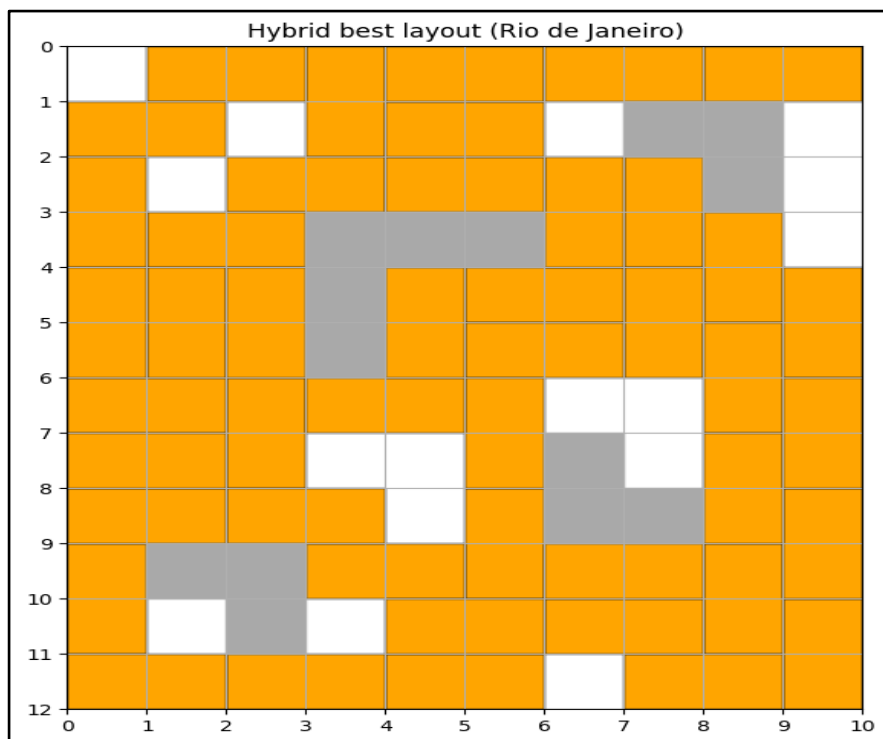


Fig. 5 Result for Rio De Janeiro for PSO-ML

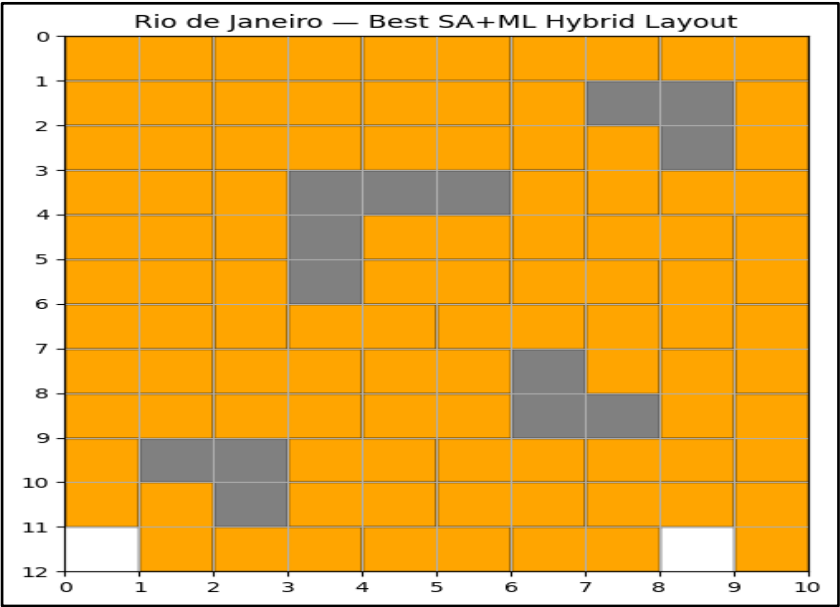


Fig. 6 Result for Rio De Janeiro for SA-ML

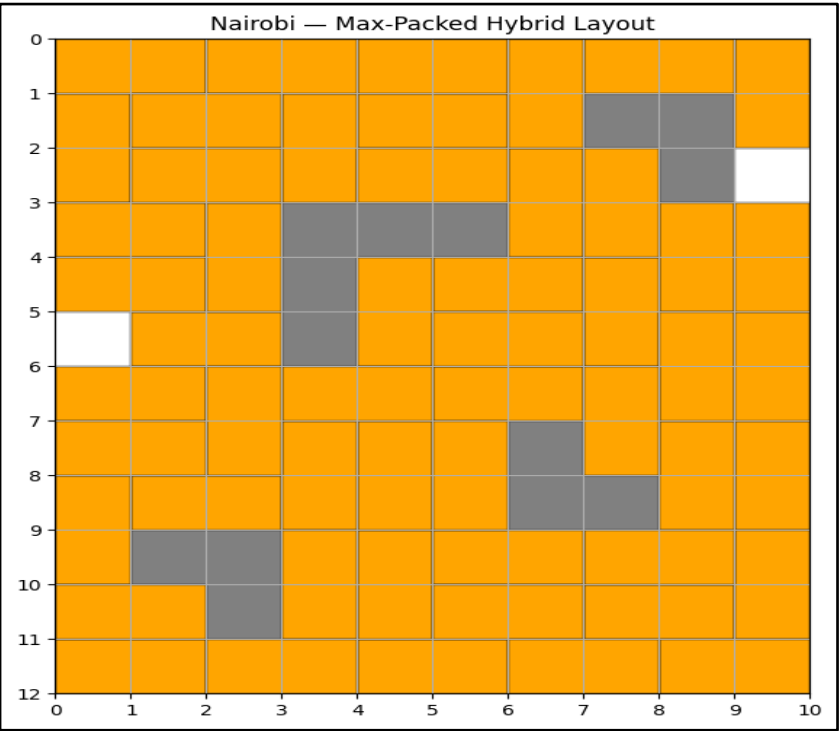


Fig. 7 Result for Nairobi for GA-ML

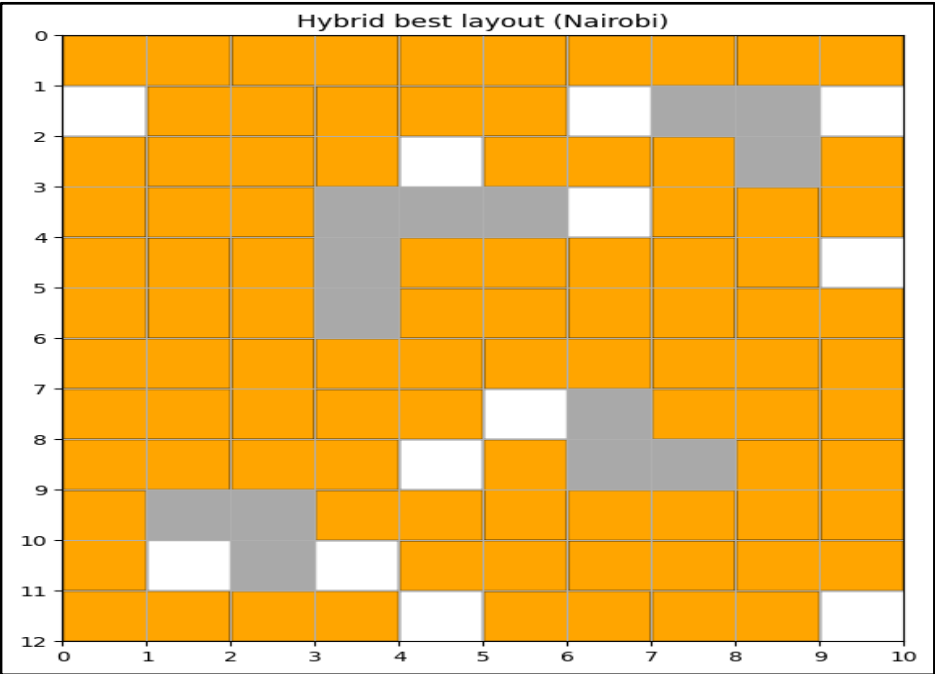


Fig. 8 Result for Nairobi for PSO-ML

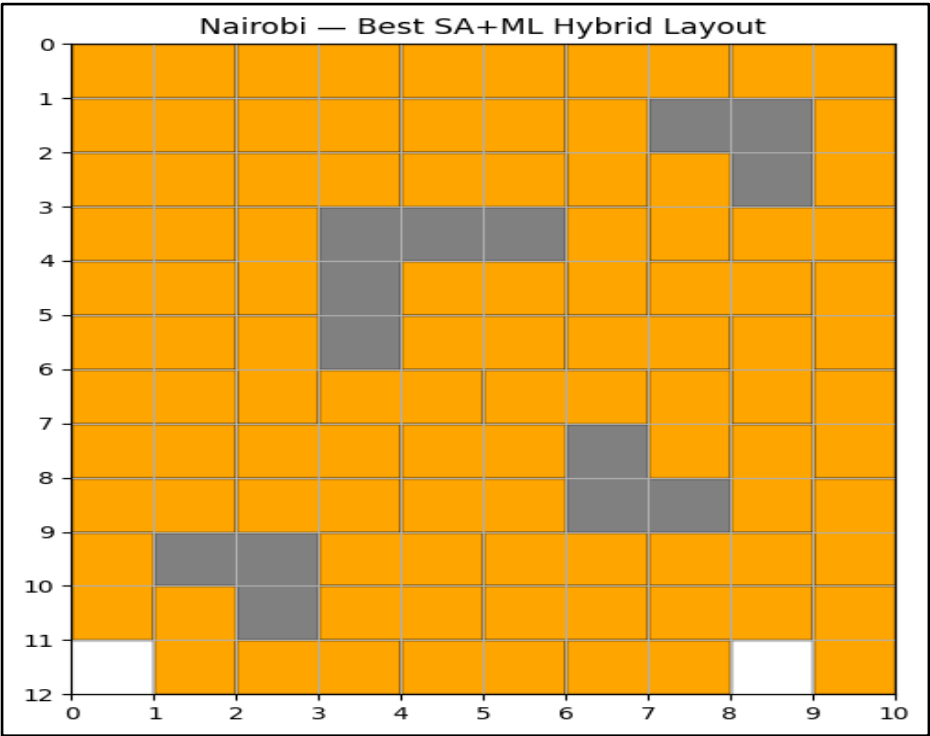


Fig. 9 Result for Nairobi for SA-ML

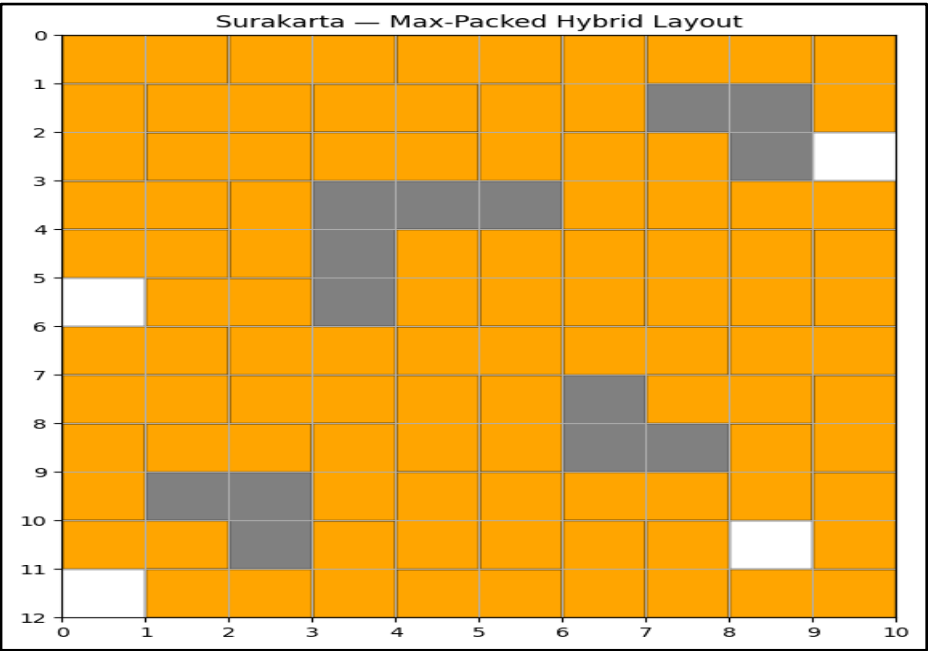


Fig. 10 Result for Surakarta for GA-ML

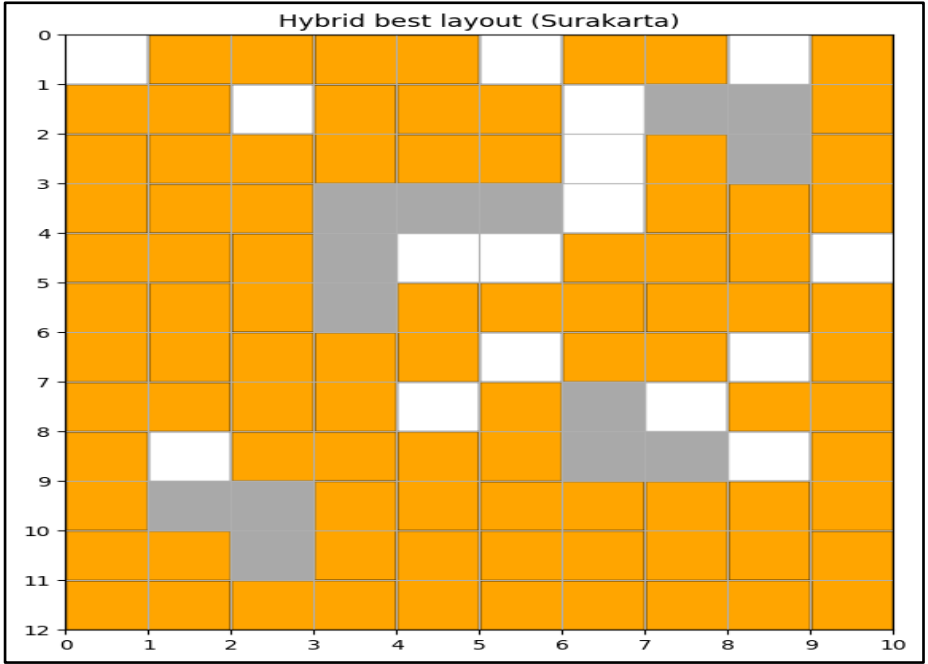


Fig. 11 Result for Surakarta for PSO-ML

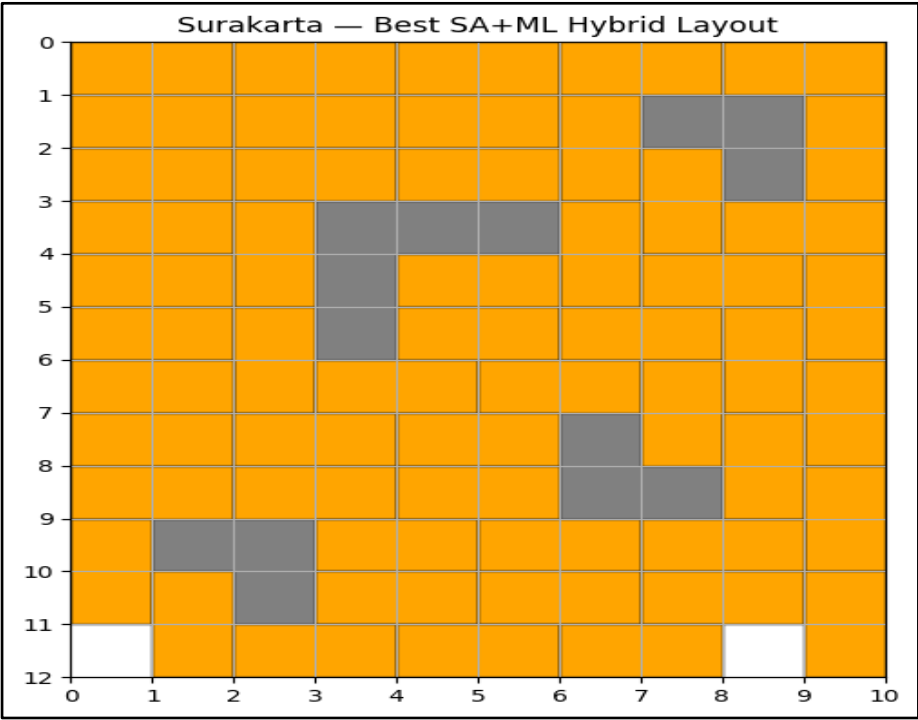


Fig. 12 Result for Surakarta for SA-ML

City	GA+ML Efficiency (%)	PSO+ML Efficiency (%)	SA+ML Efficiency (%)
Singapore	99.71	87.74	97.90
Rio De Janeiro	99.74	87.75	97.72
Nairobi	99.61	86.44	97.84
Surakarta	99.72	87.91	97.91

Table 1: Comparison of Results

The challenge of optimizing solar photovoltaic (PV) panel layouts on irregular rooftops is a complex combinatorial problem. Genetic Algorithms (GA) are known for their excellent global search capabilities, making them well-suited for maximizing the number of panels to achieve full capacity. In contrast, Particle Swarm Optimization (PSO) can be sensitive to parameter adaptation, which may lead to stagnation if not handled with adaptive inertia. Simulated Annealing (SA) is better suited for navigating complex, irregular rooftops and obstacle-laden environments, though this often comes at the expense of a slower convergence speed.

Given these trade-offs, a hybrid GA-SA solution could prove to be the most practical approach. This combination leverages GA’s robust global exploration while using SA’s superior ability to find good solutions in difficult, constrained spaces. The practical relevance of such an optimized system is significant, as efficient solar rooftop

configurations translate to enhanced household-level energy independence and are crucial for helping countries worldwide meet their ambitious renewable energy goals.

4. Conclusion

This study demonstrates that integrating machine learning surrogate models with metaheuristic algorithms provides a highly efficient approach for solar photovoltaic rooftop layout optimization. The surrogate model accurately predicted layout fitness with $R^2 \geq 0.90$, enabling faster convergence and reducing computational effort compared to standalone optimization methods. Among the hybrid frameworks, Genetic Algorithm with surrogate learning consistently achieved near-optimal performance, with efficiency exceeding 99.6% across diverse locations such as Singapore, Rio de Janeiro, Nairobi, and Surakarta. Simulated Annealing with surrogate support also performed strongly, while Particle Swarm Optimization yielded comparatively lower efficiency. The proposed framework effectively balances accuracy and computational efficiency, making it well-suited for large-scale urban PV planning. By approaching practical upper limits of rooftop PV efficiency, this work highlights the potential of surrogate-assisted optimization in accelerating renewable energy deployment and contributing to sustainable energy transition.

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DIGITALIZATION AS A DRIVER OF SUSTAINABILITY: NEW PERSPECTIVES ON ESG REPORTING

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Abstract

Sustainability is an essential concept that promotes a future in which the balance between the environment, the economy and society is maintained to ensure a better and fairer life for all. We must consider at least three essential aspects that support the importance of sustainability: environmental protection, economic benefits and social equity.

Sustainability reporting is today an essential tool through which organizations communicate their economic, social and environmental performance, providing transparency and accountability to all stakeholders.

Digitalization and the use of artificial intelligence are profoundly transforming the way companies collect, process and report sustainability-related information. These technologies not only streamline reporting processes, but also contribute to increasing the transparency, accuracy and comparability of non-financial data. As regulations become more uniform at the European level, the emergence of integrated digital platforms is expected to connect companies' ESG data with the systems of tax and financial authorities.

Keywords: Sustainability, sustainability reporting, report of sustainability, impact of digitalization.

JEL Classification: M21

1. Introduction

Sustainability is an essential concept that promotes a future in which the balance between the environment, economy and society is maintained to ensure a better and more equitable life for all. It is a collective responsibility to adopt sustainable practices in all aspects of life, from daily activities to global policies.

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Sustainability refers to the ability to maintain or support processes, systems and activities in a way that does not harm the environment, economy or society in the long term. The concept is often associated with finding a balance between the needs of the present and protecting resources for future generations. We must consider at least three essential aspects that support the importance of sustainability: environmental protection, economic benefits and social equity.

- ❑ Environmental protection: Without sustainable measures, natural resources will be depleted and the negative impact on the environment will become irreversible.
- ❑ Economic benefits: Sustainable practices can lead to long-term savings, innovation and the creation of new business opportunities.
- ❑ Social equity: Social sustainability ensures that economic resources and benefits are distributed fairly and that all people can live in a more just and balanced society.

Thus, sustainability involves an integrated approach that takes into account three essential pillars:

- a) Ecological (or environmental) sustainability refers to protecting the environment and using natural resources in a responsible way, so that they remain available and viable for the future. In this category we find: reducing greenhouse gas emissions; preserving biodiversity; managing water resources and agricultural land; promoting renewable energy and reducing dependence on fossil energy sources.
- b) Economic sustainability means creating an economic system that supports long-term prosperity, without eroding natural resources or encouraging risky financial practices. Economic sustainability includes: creating sustainable jobs; promoting economic growth that does not depend on limited resources; encouraging innovation and economic efficiency; balancing income distribution to reduce economic inequalities.
- c) Social sustainability refers to creating a fair, inclusive and stable society. This includes respecting fundamental human rights, ensuring a decent living and improving the quality of life for all people. Key aspects are: access to education and health; reducing poverty and promoting social justice; respecting cultural diversity and workers' rights; promoting active participation and community involvement in decision-making processes.

2. The Evolution of Sustainability Reporting Over Time

Sustainability reporting is today an essential tool through which organizations communicate their economic, social and environmental performance, providing transparency and accountability to all stakeholders. This practice has evolved gradually, in parallel with the development of environmental awareness and the requirements of modern society regarding business ethics.

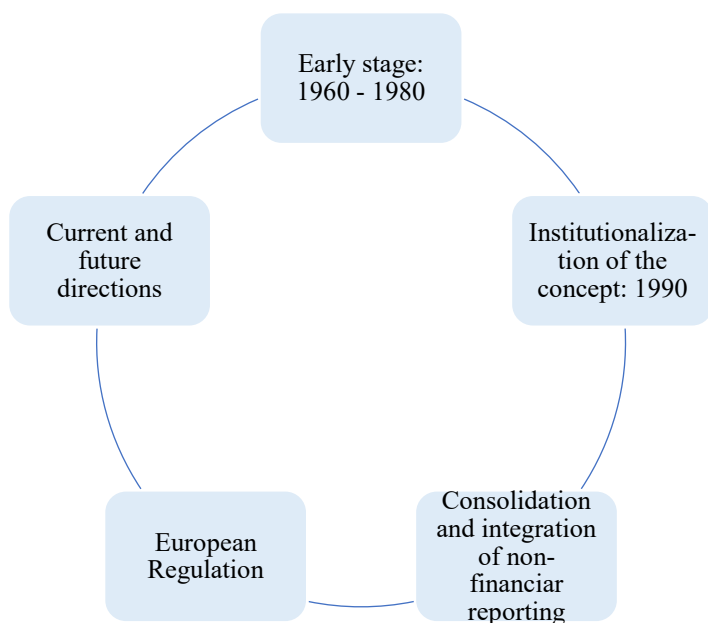


Figure 1. The Evolution of Sustainability Reporting Over Time

A) Early stage: 1960s–1980s

The first forms of reporting that can be considered precursors to sustainability reporting emerged in the context of growing environmental concerns in the 1960s–1970s. During this period, companies were increasingly accused of pollution and the irresponsible exploitation of natural resources, and public pressure led to the emergence of the first “environmental reports” — documents through which organizations tried to show that they complied with environmental protection regulations [1]. However, these reports were limited, focusing exclusively on legal compliance, not on performance or impact.

B) Institutionalization of the concept: the 1990s

The 1990s marked a turning point in the evolution of sustainability reporting. Growing awareness of climate change, as well as the globalization of capital markets, led to the need for standardization. In 1997, the Global Reporting Initiative (GRI) was launched, an international framework designed to provide companies with clear guidelines for reporting on their economic, environmental and social impacts [2]. It quickly became a global benchmark, allowing for comparability between reports from different organizations.

Also during this period, the idea of the “triple bottom line” — economic, social and environmental performance — was popularized by John Elkington, bringing a new

perspective on corporate success [3]. Companies were no longer evaluated solely on their profits, but also on their contribution to society and how they protected the environment.

C) Consolidation and Integration of Non-Financial Reporting: 2000–2010

In the 2000s, sustainability reporting began to be gradually integrated into business strategies. Publishing GRI reports became common practice for large multinational companies, and financial organizations and investors began to include ESG (Environmental, Social, Governance) criteria in investment decisions [4].

In 2010, the concept of integrated reporting was formalized with the creation of the International Integrated Reporting Council (IIRC), which promoted the idea of combining financial and non-financial information into a single strategic document [5]. This approach reflected the recognition that sustainability directly influences economic performance and long-term resilience.

D) European Regulation: 2014–2022

The European Union played a decisive role in transforming sustainability reporting from a voluntary initiative into a legal obligation. In 2014, Directive 2014/95/EU on non-financial reporting was adopted, requiring large companies to disclose information on the environment, social aspects, human rights and the fight against corruption [6]. This directive was a major step in standardizing reporting practices and increasing corporate transparency.

Subsequently, in 2022, the European Commission adopted the Corporate Sustainability Reporting Directive (CSRD), which significantly expands reporting requirements and introduces common European standards — European Sustainability Reporting Standards (ESRS) [7]. Thus, sustainability reporting has become a central element of corporate governance, not just a component of external communication.

E) Current and Future Directions

Today, sustainability reporting is closely linked to the green and digital transition. The new standards require an approach based on dual materiality — assessing the impact of the organization on the environment and society, but also how environmental and social factors influence its economic performance [8]. Technology, artificial intelligence and data analytics also contribute to increasing the accuracy and transparency of reporting.

The global trend is towards the full integration of sustainability into decision-making processes, reflecting the fact that the long-term success of an organization is inextricably linked to the health of the environment and the society in which it operates.

3. Sustainability Reporting

Globally, sustainability is supported by international agreements, such as the 2030 Agenda for Sustainable Development adopted by the United Nations, which includes the Sustainable Development Goals (SDGs). These goals address a wide range of global issues, from eradicating poverty and hunger to combating climate change and protecting ecosystems.

Sustainability reporting (also called non-financial reporting or ESG reporting) is the process by which an organization publicly communicates the impact of its activities on the environment, society and corporate governance (Environmental, Social, Governance – ESG). The main goal is to provide transparency and accountability to stakeholders — investors, employees, customers, authorities and the community — regarding how the company: uses natural resources, treats employees and communities, complies with ethical and governance principles, contributes to long-term sustainable development. Sustainability reporting typically includes three main pillars:

- ✚ Environmental: energy and water consumption, greenhouse gas (CO₂) emissions, waste management and recycling, impact on biodiversity;
- ✚ Social: working conditions and employee health, diversity and inclusion, human rights in the supply chain, community involvement;
- ✚ Governance: business ethics and integrity, governance structure, combating corruption, transparency of decisions and legal compliance.

A sustainability report is the document through which an organization communicates its economic, environmental and social impacts, as well as how it manages them. The structure and content may vary (depending on the standard used — GRI, ESRS, Romanian Sustainability Code, etc.), but in general, the recommendation is to consider the following aspects according to the table below.

Chapter	Details
Overview	☐ Declaration of the management (CEO or General Manager) about the commitment to sustainability. ☐ Organization profile: name, headquarters, main activity, shareholding structure, markets served. ☐ Sustainability context: trends, objectives, overall strategy. ☐ Reporting period and scope (entities included/excluded).
Governance and sustainability strategy	☐ Governance structure (who is responsible for sustainability, ESG committees, etc.). ☐ Policies and codes of ethics. ☐ The link between strategy and sustainability. ☐ ESG strategic objectives and key performance indicators (KPIs).

	☐ Assessment of ESG risks and opportunities.
Materiality analysis	☐ Materiality analysis process (methodology, stakeholder engagement). ☐ List of material topics (climate change, diversity, ethics, value chain). ☐ Materiality matrix (impact on the organization vs. impact on the environment/society). (The ESRS and the Romanian Sustainability Code require a “double materiality” approach – impact and financial risk.)
Stakeholder engagement	☐ Identification of the main groups (employees, customers, suppliers, community, investors, authorities). ☐ Consultation methods (surveys, interviews, partnerships). ☐ The main concerns expressed by stakeholders and the organization's response.
ESG areas	A. Environment ▪ Environmental policies and objectives. ▪ Greenhouse gas emissions ▪ Energy efficiency and energy consumption. ▪ Water consumption, waste management, recycling. ▪ Biodiversity protection. ▪ Circular economy initiatives. B. Social ▪ Workforce: number of employees, diversity, equity, workplace safety. ▪ Vocational training, health and safety. ▪ Human rights and ethics in the supply chain. ▪ Impact on local communities. ▪ Social dialogue, volunteering, donations, education. C. Governance ▪ Management structure and ESG committees. ▪ Anti-corruption policies, ethics, compliance. ▪ Data protection and cybersecurity. ▪ Transparency of decisions, financial and non-financial reporting.

Indicators, objectives, results	☐ Quantitative indicators (CO ₂ emissions, energy consumption, accident rates). ☐ Targets set and progress towards them. ☐ Comparisons with previous years. ☐ Explanations for significant variations.
Methodology and reporting standard	☐ Standards used: GRI, ESRS, SASB, Romanian Sustainability Code, etc. ☐ Limitations and calculation assumptions. ☐ Database, sources, collection methods. ☐ Verification (internal or external).
Annexes and additional information	☐ Glossary of ESG terms. ☐ Tables with detailed indicators. ☐ References to policies, certifications (e.g. ISO 14001, ISO 45001). ☐ Contacts for feedback.

Table 1: A sustainability report model

In the European Union, sustainability reporting is mandatory for certain companies through:

- CSRD (Corporate Sustainability Reporting Directive) – gradually applicable from 2024–2026;
- ESRS (European Sustainability Reporting Standards), which establish the specific reporting method.

At the international level, other standards are also used such as:

- GRI (Global Reporting Initiative)
- SASB (Sustainability Accounting Standards Board)
- TCFD (Task Force on Climate-related Financial Disclosures)

EU Directive 2022/2464 (known as the Corporate Sustainability Reporting Directive - CSRD) establishes that large companies must report information on sustainability (environment, social, governance). In Romania, the Order of the Ministry of Public Finance no. 85/2024 defined the deadlines for the application of sustainability reporting for the entities concerned. The Romanian Sustainability Code was also established as a voluntary, but reference, instrument for entities wishing to report in the field of sustainability. The Romanian Sustainability Code Platform provides support for entities, including those not legally obliged, to prepare the report. Sustainability reporting in Romania goes through the following stages:

- ✓ From January 1, 2024, public interest entities, such as listed companies or parent companies of groups, that have over 500 employees, prepare a sustainability report for the financial year 2024 (published in 2025).
- ✓ From January 1, 2025, the obligation is extended to medium/large entities with over 50 employees and that meet the criteria of turnover (over 50 million lei) and assets (over 25 million lei). The related report will be prepared in 2026.)
- ✓ From January 1, 2026, the obligation will also be extended to listed SMEs, the report being published in 2027.

The Romanian Sustainability Code represents a methodology for sustainability reporting in Romania. It provides clear guidance on the content and process of preparing sustainability reports for entities. It was adopted by Government Decision no. 1117/2023 (Methodology for sustainability reporting – Romanian Sustainability Code – CRS). Its purpose is to meet legislative obligations regarding non-financial reporting and sustainability, in the European and national context. The CRS also has the role of increasing the transparency, comparability and accessibility of sustainability data reported by entities, but also of supporting entities in preparing sustainability reports. It is mandatory for entities that, at the balance sheet date, exceed 500 employees during the financial year to submit a sustainability report. These entities have a legal obligation to prepare a non-financial statement that includes at least: environmental, social and personnel aspects, respect for human rights, combating corruption and bribery. However, this type of report can be submitted voluntarily by any other entity (smaller companies, public or private sector entities) that wishes to voluntarily report information on sustainability.

The following table details the sustainability reporting requirements:

Country	Requirements
United States	There is no single federal law, but: The SEC (Securities and Exchange Commission) is proposing mandatory climate reporting rules for listed companies. Many companies voluntarily report according to SASB, GRI or TCFD. Institutional investors (e.g. BlackRock) are already demanding detailed ESG data.
Canada	ESG reporting is gradually becoming mandatory for financial institutions and listed companies. Aligns with TCFD and ISSB.
United Kingdom	Large companies must report non-financial information (climate, energy, governance). Standard: TCFD (Task Force on Climate-related Financial Disclosures) – mandatory for listed companies from 2022.

	Transition to the new ISSB (IFRS Sustainability Disclosure Standards) framework is being prepared.
Japonia	Mandatory ESG reporting for listed companies; guidelines from the Financial Services Agency
China	Climate reporting obligations for large state-owned companies; ESG standards in development.
South Korea	Mandatory ESG reporting for listed companies by 2030.
Australia	Mandatory climate reporting rules from 2025 for large companies
Brazilia	B3 Stock Exchange requires listed companies to publish ESG reports
Chile	TCFD rules implemented for financial companies
Africa de Sud	Since 2010, companies listed on the Johannesburg Stock Exchange have been required to publish integrated reports (financial + ESG).
United Arab Emirates, Saudi Arabia, Qatar	They have ESG rules in development for listed companies.

Table 2: Details regarding sustainability reporting

4. The Impact of Digitalization and Artificial Intelligence on Sustainability Reporting

Digitalization and the use of artificial intelligence are profoundly transforming the way companies collect, process, and report sustainability information. These technologies not only streamline reporting processes, but also contribute to increasing the transparency, accuracy, and comparability of non-financial data.

If in the past non-financial data was collected manually, fragmentedly and often without uniform standards, digital technologies today allow the automation of the entire workflow. IoT devices, monitoring platforms and integrated ERP systems collect information on resource consumption, emissions, waste management or social performance in real time, considerably reducing errors and operational costs. In addition to digitalization, artificial intelligence plays an essential role in processing large volumes of data, identifying patterns and generating relevant insights. Machine learning algorithms can predict future developments in environmental indicators, detect anomalies or areas with high negative impact and provide recommendations for optimizing ESG (Environmental, Social, Governance) strategies. This advanced analytical capacity not only streamlines internal processes, but also supports the adoption of informed decisions, aligned with sustainability objectives.

In addition, technological solutions facilitate increased transparency, accuracy and comparability of non-financial data. Digital platforms enable standardized reporting in accordance with the requirements of legislation and international frameworks such as CSRD, GRI or SASB, and artificial intelligence-based tools can verify data consistency and

generate automated reports. Thus, organizations provide stakeholders with more credible and easily assessable information, which is essential for building trust and attracting responsible investments. Overall, digitalization and artificial intelligence are not just technical tools, but strategic elements that support the sustainable transformation of companies. They enable stronger governance, continuous monitoring of ESG performance and rapid adaptation to the increasingly complex requirements of the business environment and society.

i) Automate data collection and processing

Sustainability reporting involves a considerable volume of data from various sources: energy consumption, carbon emissions, waste management, supply chain, employee data or corporate governance. Through digitalization, this information can be collected automatically, in real time, through ERP systems, IoT (Internet of Things) and integrated analytics platforms [9]. Artificial intelligence facilitates the processing of this data, identifying relevant patterns, inconsistencies or trends. For example, machine learning algorithms can estimate indirect emissions (scope 3) or assess climate risks in supply chains, reducing the time and costs associated with manual reporting [10]. Some of the most important climate risks in supply chains, grouped by categories [15, 16], are: acute physical risks (extreme events), chronic physical risks (progressive changes), transition risks, reputational risks, operational and logistical risks, Risks related to dependence on vulnerable suppliers.

The most important climate risks in supply chains:	Examples:
■ Acute physical risks (extreme events), these are immediate effects of extreme weather phenomena on the supply flow.	• Floods that destroy factories, logistics centers or transportation routes; • Storms, hurricanes, tornadoes that affect port and maritime infrastructure; • Heat waves that reduce the productivity of factory workers or increase the rate of equipment failure; • Wildfires that disrupt access to raw materials; • Severe droughts that limit agricultural production.
■ Chronic physical risks (progressive changes), these gradually affect	• Increase in average temperatures, which reduces crop yields; • Depletion of water resources, affecting the food, textile and chemical industries;

production capacity and costs.	• Rising sea levels, threatening factories located in coastal areas; • Degradation of soil quality, with an impact on agricultural raw materials; • Change in climate zones, which forces production to move to other regions.
■ Transition risks that are generated by legislative, technological and market changes necessary for the transition to a low-emission economy.	• Strict emissions regulations that increase suppliers' costs; • Increased demand for "green" materials, which can create shortages in sustainable raw material markets; • Restrictions on certain polluting substances or processes, forcing companies to change their suppliers; • Rising energy costs for fossil fuel-dependent suppliers; • Changes in ESG standards requiring additional investment in reporting and compliance.
■ Reputational risks	arise when supply chain partners do not comply with climate or social requirements. • Suppliers that do not comply with environmental standards, which can affect brand image; • Lack of transparency on Scope 3 emissions; • Negative disclosures regarding upstream pollution or environmental degradation.
■ Operational and logistical risks with a direct impact on material flows and business continuity.	• Transport delays caused by extreme weather events; • Increased transport costs due to longer alternative routes; • Low availability of raw materials from climate-affected areas; • Price volatility due to reduced production in certain regions.
■ Risks related to dependence on vulnerable suppliers	• Single suppliers located in areas with high climate risk; • Concentration of production in regions exposed to drought, flooding or extreme weather cycles; • Lack of suppliers' climate continuity plans.

Table 3: The most important climate risks in supply chains

ii) Increasing accuracy and transparency

One of the great advantages of AI is the ability to ensure traceability and verifiability of data. Blockchain and AI-based platforms can guarantee the integrity of reported information, providing a secure and digitally audited system for verifying ESG performance [11]. This makes reporting more credible and less susceptible to errors or intentional manipulation (“greenwashing”). Digitalization also allows for the automatic correlation of indicators with relevant standards, such as the European Sustainability Reporting Standards (ESRS) or the Global Reporting Initiative (GRI), reducing the risk of legislative non-compliance [12].

iii) Predictive analytics and decision support

Artificial intelligence is not limited to reporting on the past, but provides predictive analytics on future sustainability performance. Companies can simulate the impact of climate scenarios on their operations or estimate the costs of transitioning to climate neutrality.

By analyzing ESG data, AI can identify emerging risks and green investment opportunities, supporting strategic management decisions [13].

iv) Digitalization of CSRD and ESRS reporting

The new European requirements (CSRD and ESRS) encourage the adoption of a standardized digital reporting framework. Sustainability reports will have to be published in electronic format, using digital tags (XHTML and XBRL), to allow for automated processing and comparison of data at European level [7]. This digital transformation will facilitate surveillance, analysis and comparability between companies, investors and authorities.

5. Conclusions

While the benefits are significant, digitalization and AI also bring challenges. IT system integration, data security, lack of digital skills and upfront costs can limit the rapid adoption of these technologies, especially for SMEs.

Furthermore, over-reliance on algorithms can generate ethical risks — for example, decisions based on incomplete data or algorithmic bias [14]. Therefore, digital governance and accountability in the use of AI become essential for the credibility of sustainability reporting.

As regulations become more uniform across Europe, integrated digital platforms are expected to emerge that connect companies’ ESG data with tax and financial authority systems. AI will increasingly become a strategic partner, not just a technological tool,

capable of supporting companies' transition to sustainable and circular business models. Thus, ESG is becoming mandatory for large companies in most developed countries. There is a global harmonisation between the standards: ESRS (EU) and ISSB (global). Investors and banks use ESG data to assess companies' risk and performance. Digital reporting will become the norm in the coming years.

Over 80 countries now have rules or recommendations on sustainability reporting.

The global trend is clear: moving from voluntary reporting to mandatory reporting.

Key standards used internationally: GRI – the most widespread globally; TCFD / ISSB (IFRS S1 & S2) – for climate and governance; ESRS (EU) – the most complete and detailed current framework.

Experts estimate that, by 2027, over 90 countries will have a formal ESG reporting framework, and the ESRS (EU) and ISSB (global) standards will become the common language of sustainability in the world.

In conclusion, we see that the most important developments and trends in sustainability reporting could be:

- Stronger regulation and expansion of obligations, as well as the expansion of entities subject to reporting;
- Convergence between international standards (ISSB) and impact standards (GRI, ESRS); there are active efforts for interoperability between them to reduce duplication of reporting.
- Verification requirements for sustainability information will become mandatory in principle in more and more jurisdictions (notably the EU); thus, financial auditors or third parties will have to attest to ESG data.
- Sustainability reporting will move to structured digital formats for comparability and integration with financial reports.
- Reporting on emissions and risks in the value chain (Scope 3) remains central — even if in some regions the exact requirements for Scope 3 are still debated or even contested.
- In addition to climate, new standards will increasingly address issues such as biodiversity, land use, workers' rights and impact on communities.
- There will be increasing pressure to connect non-financial information with financial information — risk and financial impact, scenarios, capital assessments.

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A CPM-BASED FRAMEWORK FOR MANAGING DIGITAL TRANSFORMATION IN SMART LABS

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Abstract

This study proposes a conceptual framework for implementing smart laboratory platforms, integrating the Critical Path Method (CPM) to optimize development timelines and resource allocation. The framework addresses the design, sequencing, and interdependencies of digital infrastructure components, ensuring alignment with institutional objectives and research needs. By modeling tasks as a directed acyclic graph, CPM identifies the sequence of activities that determine the minimum completion time, distinguishes critical from non-critical tasks, and quantifies scheduling flexibility. A case study demonstrates the application of CPM in planning a smart lab platform, highlighting key dependencies, potential bottlenecks, and opportunities for workload balancing. The findings provide actionable insights into project scheduling, risk management, and stakeholder coordination, offering a structured methodology adaptable to diverse institutional contexts.

Keywords: smart labs, critical path method, workflow optimization, digital infrastructure

JEL Classification: O32

1. Introduction

The transition toward smart laboratories is driven by the increasing integration of digital technologies, automation, and data-driven decision-making in research environments. These platforms combine hardware, software, and networked services to enhance operational efficiency, enable remote collaboration, and support complex experimental workflows. However, the deployment of such systems presents significant challenges, including the coordination of multiple interdependent tasks, alignment with institutional strategies, and the optimization of time and resource allocation.

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This study addresses that gap by proposing a conceptual framework that integrates digital infrastructure planning with workflow optimization using the Critical Path Method (CPM). Rather than serving merely as a project management tool, CPM is applied as a process modeling technique to capture task dependencies, sequence activities logically, and identify implementation bottlenecks. The resulting framework spans technical, operational, and organizational layers, offering a scalable and interoperable model for planning and deploying smart labs. This contribution advances existing literature in project scheduling, research infrastructure, and digital transformation by introducing formal process dependency analysis into laboratory design.

To facilitate a structured analysis, the article is organized into several key sections. It begins by contextualizing smart laboratories within the broader landscape of digital transformation and research infrastructure. It then presents the theoretical foundation and modeling rationale, followed by a detailed explanation of the proposed framework, the use of CPM, and the implications for implementation and scalability. The final sections discuss the practical significance, limitations, and directions for future empirical validation.

From a practical perspective, the framework provides a planning and management tool for laboratory designers, IT architects, and academic institutions. It supports better coordination, scheduling, and integration of digital components while enabling modular development, operational flexibility, and institutional scalability.

To structure this investigation, the study pursues three primary objectives:

- to develop a conceptual framework for the design and implementation of smart lab environments, integrating digital infrastructure with workflow optimization;
- to apply CPM as a modeling technique to map dependencies, identify bottlenecks, and optimize resource allocation;
- to analyze existing frameworks and propose an integrated solution that enhances scalability, interoperability, and operational efficiency in smart lab systems.

Methodologically, this research follows a qualitative, design science approach, grounded in conceptual frameworks and informed by a synthesis of relevant literature. Workflow mapping is used to visualize how hardware, software, and data systems are integrated within the smart lab environment. The resulting framework spans technical, operational, and organizational layers, offering a coherent model that is adaptable to institutional realities.

Although conceptual at this stage, the framework is consistent with design science research standards and provides a transferable foundation for future empirical validation. It offers both a theoretical advancement in structured smart lab planning and a practical tool for institutions undergoing digital transformation. Unlike existing procedural guides or case-specific implementations, this framework introduces a generalizable, theory-driven methodology for planning smart labs.

2. Literature review

2.1 Smart labs: virtualization and digitalization

In this study, a smart laboratory refers to a digitally integrated research environment that combines hardware, software, and data infrastructure to support real-time, collaborative, and automated research processes.

Smart laboratories increasingly utilize IoT, AI, and digital technologies to support adaptive experimentation and scalable learning [1]. Their growing complexity necessitates not only advanced infrastructure but also structured educational approaches. To address this, Zamiri et al.[2] propose a training toolkit to integrate Smart Labs into academic curricula, aligning with learner and institutional needs. Modularity and interoperability are also key, as Gawer [3] argues, to support cross-institutional collaboration and innovation. Additionally, Zvobgo [4] emphasizes the need for stakeholder alignment, governance, and outcome-based planning. These insights collectively advocate for a holistic smart lab framework that integrates technological, pedagogical, and strategic elements to enhance educational and research outcomes.

The SMART-UHA Project [5] underscores the integration of university campuses as open innovation ecosystems where students, researchers, and industries co-develop technologies in real-world contexts. It emphasizes participatory engagement and modular infrastructure, aligning with our framework's emphasis on stakeholder involvement and interoperability.

Zheng et al. (Zheng et al., 2019) propose an IT-driven co-creation paradigm through “smart, connected open architecture products,” advocating for lifecycle personalization and dynamic reconfiguration. Their model supports our framework's scalability and modularity, especially in terms of adapting digital platforms to user needs and extending smart lab capabilities across the research lifecycle.

The Siemens roadmap [8] and the U.S. DOE Smart Labs initiative [9] both highlight infrastructure readiness and energy efficiency but lack comprehensive methodologies for integrating digital tools with research workflows. These sources validate our argument for a structured implementation framework that merges project scheduling with technological architecture.

Backlund et al. [10] highlight the challenges of implementing smart labs in multipurpose environments, pointing to the necessity of pilot testing, stakeholder co-creation, and infrastructure adaptability. This reinforces our proposal to empirically test the conceptual model through simulations and pilot programs.

Bygholm and Kanstrup [11] critique the participatory models in living labs, suggesting that without structured methodologies, engagement remains superficial. This lends further

weight to our framework's layered approach, where design science principles ensure systematic stakeholder engagement and repeatable planning models.

Smart laboratory implementation faces several challenges. Key among them is the need to enable remote operability and multi-user access, which underscores the importance of automation and digitalization [12]. Additional barriers include limited access to necessary electronic components, regulatory constraints on imports, procurement delays, and unstable internet connectivity [13].

2.2. Frameworks in Smart Labs

Despite a growing body of case studies [14] and institutional initiatives on smart lab development, the literature still lacks comprehensive, generalizable frameworks that integrate key elements such as scheduling logic, interoperability, and stakeholder engagement. While standards like ISO/IEC 15288 and the SiLA [15] interface emphasize lifecycle management and semantic interoperability, they are rarely applied in practice to guide smart lab implementation. Existing models often focus narrowly without addressing platform orchestration or integrated workflows.

Major industry reports, like those from Siemens [8], underscore the importance of infrastructure modernization but stop short of offering holistic methodologies for aligning digital infrastructure with research-specific needs. Similarly, the I2SL Smart Labs Toolkit [14] prioritizes energy and ventilation optimization over collaborative or scalable implementation models. Projects often begin with retrofitting existing infrastructure, leading to compatibility issues with legacy systems and fragmented interfaces [16], [17].

To address these theoretical and methodological limitations, this study introduces a CPM-based framework that bridges digital infrastructure planning with structured process execution, offering a more repeatable and adaptable approach for the development of smart laboratories.

2.3. The Context and Value of CPM in Smart Labs

CPM provides a structured approach for managing the complexity of smart lab development, where system interoperability, digital infrastructure, and testing phases are highly interdependent. Originating in the 1950s from engineering and construction project management [18], CPM identifies the longest sequence of dependent activities to determine the minimum project duration [19].

While CPM does not address concurrent scheduling or resource constraints, it remains essential in identifying bottlenecks and prioritizing critical tasks. This makes it particularly valuable for digital transformation initiatives like smart labs, where delays in key

implementation stages—such as system integration or testing—can disrupt the entire timeline [20], [21], [22]. Zheng et al. [23] in their review on smart manufacturing systems for Industry 4.0, argue for integrating modular platforms and AI-driven optimization. Their perspective supports the adoption of scheduling tools like CPM for enhancing task prioritization and process automation in smart labs.

3. Methodology

The research design combines two complementary methodological components: literature-based conceptual synthesis and dual-layered process modeling. A structured literature review was conducted to identify current challenges, implementation strategies, and technological best practices in smart lab development. The review focused on areas such as digital infrastructure design, workflow optimization in research contexts, and the application of scheduling methodologies in complex environments.

- **Task Identification and Structuring:** Project activities were defined based on institutional requirements, technical specifications, and stakeholder input. Eleven major tasks were identified, covering hardware/software acquisition, technical requirements specification, technology development, platform security, data management, authentication, user interface design, system integration, testing, protocol development, and deployment with training.
- **Dependency Mapping:** A directed acyclic graph was constructed, where each node represented an activity and each edge indicated a dependency. This ensured logical sequencing by linking each task to its immediate predecessors and successors. The structure also allowed for the identification of concurrent and sequential tasks, enabling the differentiation between critical and non-critical activities.
- **Duration Estimation:** Published literature and industry reports on smart laboratories and digital infrastructure initiatives were consulted to extract typical implementation patterns, expected challenges, and development timelines. These sources helped refine both the activity categories and their temporal expectations, ensuring that the framework reflects practical constraints and industry norms.
- **Critical Path Analysis:** A forward pass calculation determined the earliest start (ES) and earliest finish (EF) for each activity, while a backward pass established the latest start (LS) and latest finish (LF) times. Total float was computed as the difference between LS and ES (or LF and EF). Activities with zero float were identified as critical.

The analysis revealed a critical path with a total duration of 23 months. Non-critical activities exhibited float values that allow rescheduling without affecting the overall completion date. This distinction provides opportunities for resource leveling and risk mitigation.

The resulting CPM diagram (Figure 2) and Gantt chart (Figure 3) visually represent the temporal and logical structure of the project, enabling clear communication of scheduling priorities to all stakeholders.

4. Results and discussions

The smart lab platform, as defined in this study, refers to the integrated digital infrastructure that supports and enhances the operation of laboratory workflows, including data management, task scheduling, and inter-system communication.

The proposed framework consists of five key implementation phases: (1) infrastructure and component assessment, (2) technology development and standardization, (3) security and access control, (4) system integration and implementation, and (5) testing and validation. Each phase is structured using CPM-based workflow modeling. The logical sequence of tasks, their interdependencies, and durations are represented through a directed acyclic graph to identify the critical path and optimize scheduling.

4.1. Structuring activities for a smart lab platform

The diagram presents the structured process extracted from the literature that we followed in designing the smart lab framework, divided into five key stages: infrastructure assessment (identifying technical readiness), development and standardization (aligning hardware/software), security and access control (data protection, access governance), system integration and implementation (platform assembly), and testing and validation (system performance). This visual representation reflects our conceptual model and serves to clarify the logical sequence and interdependencies between development tasks, as seen in Figure 1 below.

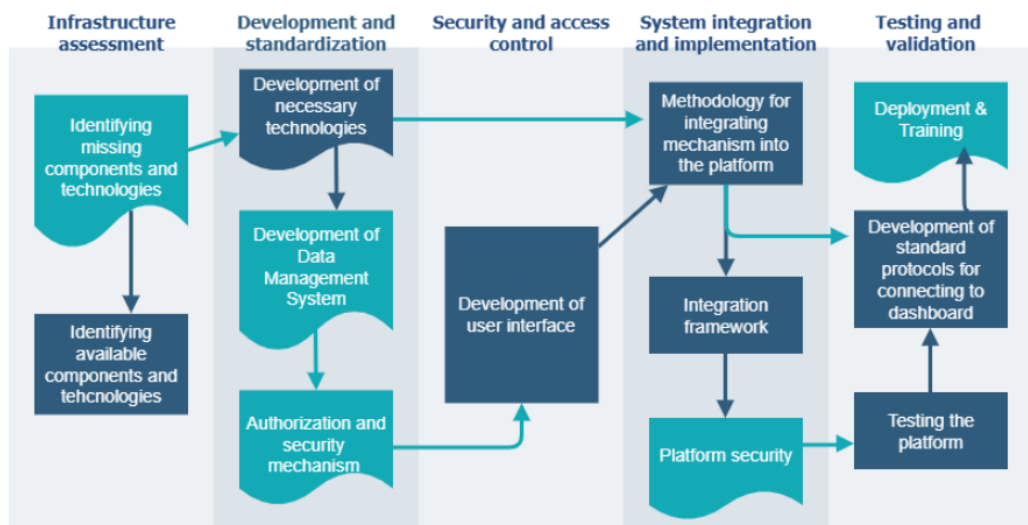


Figure 1. Key principles of a smart lab platform development workflow³

The conceptual model begins with **Infrastructure and Component Assessment**, which involves a comprehensive analysis of the existing infrastructure to identify both available and missing components, technologies, and potential integration points. This diagnostic step focuses on uncovering gaps in hardware, software, and connectivity that may affect system performance. The primary objective is to minimize development costs and reduce implementation time by leveraging existing resources while ensuring scalability and functionality of the platform.

In the **Technology Development and Standardization** phase, the necessary technologies are designed and developed to bridge the identified gaps. This phase emphasizes advancements in both hardware and software capabilities, the integration of AI-driven modules for automation and optimization, and the support for platform scalability. These foundational elements are essential to enable collaborative research and data-driven experimentation.

The **Security and Access Control** stage prioritizes the implementation of a robust authorization mechanism to manage authentication and role-based access. A user interface is developed to support intuitive navigation, secure experiment monitoring, real-time system interaction, and efficient access management. This interface serves as a bridge between users and the core infrastructure, ensuring usability alongside data protection.

During **System Integration and Implementation**, a standardized methodology is applied to integrate all platform components. This ensures technical compatibility across diverse hardware, software modules, communication protocols, and network systems. Security measures such as encryption, firewall protection, threat detection systems, and vulnerability assessments are implemented to preserve data confidentiality, integrity, and availability.

The final stage, **Testing and Validation**, includes the development of standardized communication protocols that enable seamless interaction between data sources, AI tools, and the user dashboard. A key outcome of this phase is the creation of an interactive dashboard that supports real-time experiment tracking, data analytics, and centralized reporting. This component enhances laboratory oversight and facilitates informed decision-making and efficient research execution.

4.2. Critical path method in smart lab platform development

To operationalize the planning logic, we developed a process framework based on CPM, detailed below.

The CPM activity set for smart lab implementation was developed through a systematic project management and systems engineering approach. Functional requirements were first identified—hardware setup, software development, data management, user interface design, integration, testing, and deployment—and translated into sequential, interdependent

³ Realized using Draw.io <https://draw.io>

tasks. Dependencies were mapped using a directed acyclic structure, ensuring that prerequisite components, such as security systems and dashboards, follow foundational infrastructure development. Activity durations, estimated in months via expert input and benchmarks, reflect varying complexity, from short requirement identification phases to longer technology development stages. Eleven activities (A–K) were defined, with the critical path $A \rightarrow C \rightarrow D \rightarrow G \rightarrow H \rightarrow I \rightarrow K$ determining the minimum project duration. This framework enables precise scheduling, highlights bottlenecks, and prioritizes zero-slack tasks to safeguard overall project timelines.

Activity ID	Activity (edges)	Dependency	Length (months)
A	Identify necessary hardware and software components	-	2
B	Authorization & Security Mechanism Development	A	3
C	Identification of Required Components & Technologies	A	2
D	Development of Essential Technologies	C	8
E	Development of Data Management System	A	5
F	User Interface & Dashboard Design	B	4
G	Platform Security Implementation	C, D	5
H	Integration of All Components into the Platform	E, F, G	1
I	Testing & Validation of the Smart Lab	H	3
J	Development of standard protocols for connecting to the dashboard	H	3
K	Deployment & Training	I, J	2

Table 1. Activity List with Dependencies and Estimated Durations for Smart Lab Platform Implementation.

However, to visualize these dependencies and structure workflow execution, we need a graph-based process model, as discussed in the next section.

4.3. Complex process modeling for smart lab platform

Building on the critical path structure identified in the previous section, we developed a graph-based process model to simulate the sequence and dependencies of smart lab implementation tasks.

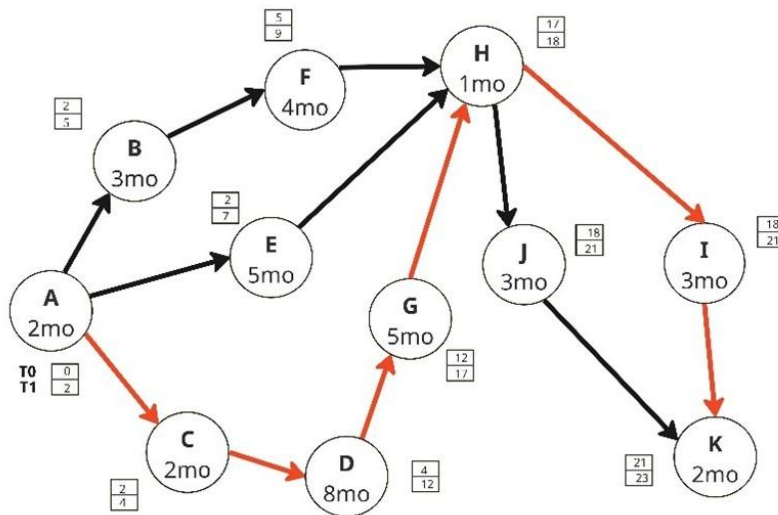


Figure 2. Critical Path Diagram: Visualizing task interdependencies and timeline (A–K) in smart lab platform implementation.⁴

To enhance the clarity and analytical depth of process modeling, the critical path analysis was supplemented with a detailed CPM diagram. The Critical Path Method is a formal project management technique widely used in engineering and operations planning to model the structure, timing, and dependencies of interrelated activities. In the context of smart lab development, the CPM diagram clearly represents task sequences, durations, and the distinction between critical and non-critical activities. Unlike simple workflow charts, CPM diagrams explicitly display logical task relationships, highlight the longest path through the project network, and indicate where float (slack) exists. This allows for precise coordination of activities such as user interface development, platform security, or integration under defined timing constraints.

The diagram in Figure 2 was constructed as a directed acyclic graph, where each node represents an activity and each directed edge denotes a dependency. Activity durations were estimated using expert input and comparable project timelines, assuming fixed resource availability and sequential execution. The CPM computation identified the critical path as

⁴ Realized using Miro <https://miro.com>

$A \rightarrow C \rightarrow D \rightarrow G \rightarrow H \rightarrow I \rightarrow K$, with a total project duration of 23 months. All activities on this path exhibit zero total float, indicating that any delay will directly extend the project completion date.

Forward and backward pass calculations identified significant float in non-critical activities: E (Data Management, 10 months), B (Authentication & Security, 8 months), and F (UI & Dashboard, 8 months). These tasks can be rescheduled or resource-leveled without affecting overall delivery, provided they are completed by their latest start times (E: month 12, B: month 10, F: month 13). In contrast, D (Develop Technology) and G (Platform Security) represent primary bottlenecks due to their extended durations and critical positioning, while H (Integration) serves as a key convergence point for downstream processes I (Testing) and J (Protocol Development). Although J is non-critical, its timely execution remains essential for synchronized deployment alongside testing outputs.

This interpretation supports three strategic management actions:

- Prioritize resources for D and G to mitigate risks of delay.
- Leverage float in E, B, and F to optimize workload distribution.
- Implement readiness gates at H and I to ensure prerequisites are met before initiating dependent activities.

This CPM assessment not only quantifies the minimum feasible completion time but also provides actionable insights into schedule flexibility, resource allocation, and risk concentration, enabling data-driven decision-making for efficient project execution.

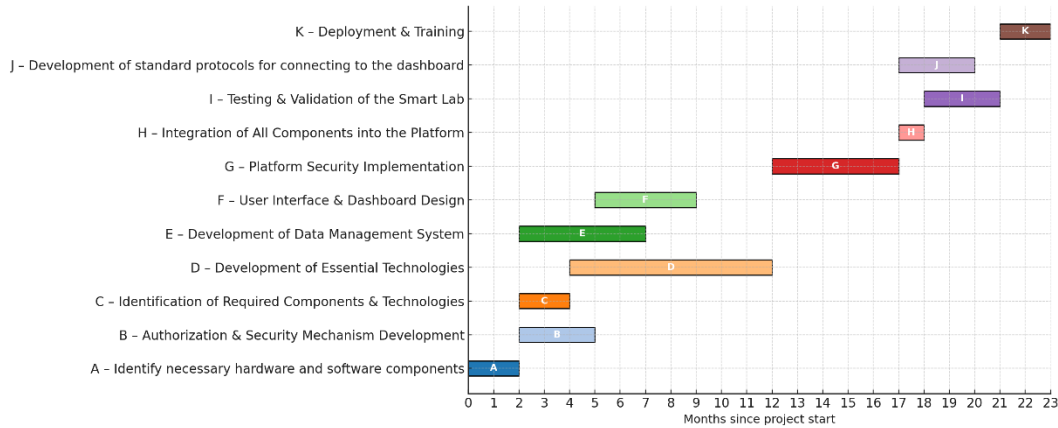


Figure 3: Gantt Chart for Smart Lab Implementation based on CPM Analysis

The Gantt chart in Figure 3 translates the CPM network into a time-scaled visual schedule, showing each activity's duration, start and end dates, and dependencies in a linear format. Critical path activities are highlighted to emphasize their impact on the overall schedule, while non-critical tasks are shown with their available slack. This visualization enables stakeholders to monitor progress, adjust non-critical activities, and focus resources on preventing delays in critical path tasks.

4.4. Implementation Considerations

Successful deployment of a smart lab platform requires more than technical integration; it also demands institutional alignment and coordinated stakeholder engagement. Key actors, including institutional leadership, IT personnel, lab coordinators, researchers, and administrative staff must align implementation with broader organizational goals across both operational and governance layers of the proposed framework.

Institutional leaders guide strategic planning and ensure policy alignment, while IT teams manage system interoperability and cybersecurity. Lab coordinators oversee functional workflows, and researchers contribute domain-specific requirements for experimental design and data handling. Involving these stakeholders early, particularly during infrastructure assessment and workflow design, enhances user adoption, promotes iterative refinement, and ensures long-term sustainability through compliance and governance integration.

5. Conclusions

This study introduces a conceptual framework for the digital transformation of smart laboratories, integrating the Critical Path Method (CPM) with workflow design and digital infrastructure strategies. The framework provides a scalable, secure, and interoperable roadmap for managing complex research environments and improving operational efficiency, resource allocation, and data integration.

The originality lies in adapting project scheduling techniques—traditionally used in industrial and construction domains—to smart lab implementation. By mapping dependencies and critical processes, our framework supports coordinated planning, risk mitigation, and modular deployment across diverse technical ecosystems.

Unlike existing models such as the I2SL Smart Labs Toolkit or the Siemens SmartLab Roadmap, which emphasize infrastructure and safety, this CPM-based approach introduces a process-oriented dimension that enables quantifiable monitoring of implementation performance and proactive identification of bottlenecks.

Future validation should involve empirical testing and scenario-based simulations under varying resource constraints. Suggested key performance indicators include reduced workflow setup time, improved resource utilization, increased system uptime, and measurable cost savings.

Ultimately, the framework offers both theoretical and practical value, complementing existing smart lab initiatives while advancing structured, data-driven methodologies for next-generation research infrastructures.

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INNOVATION IN THE EUROPEAN UNION: DESCRIPTIVE ANALYSIS OF EMERGING INNOVATORS, WITH A FOCUS ON ROMANIA

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Abstract

Innovation plays a key role in driving economic growth, competitiveness, and social progress. The European Innovation Scoreboard (EIS) provides a comprehensive framework for assessing how countries advance in this area. This study examines the group of Emerging Innovators in 2025 — Bulgaria, Hungary, Latvia, Poland, Romania, and Slovakia — with particular attention to Romania. Within this group, Romania shows notable improvement over time, yet continues to face structural challenges that limit convergence with the EU average. Using the Summary Innovation Index (SII), performance changes, annual gaps, and Compound Annual Growth Rates (CAGR), we compare Romania's trajectory with that of Croatia and the EU27. The analysis highlights areas where Romania is catching up, as well as those where persistent weaknesses remain, offering a clearer picture of its position and progress within the European innovation landscape.

Keywords: innovation performance, Summary Innovation Index (SII), Emerging Innovators, Compound Annual Growth Rate (CAGR)

JEL Classification: M15

1. Introduction

Innovation is a central driver of growth, competitiveness, and societal development, and the European Innovation Scoreboard (EIS) [1] provides a valuable framework for assessing countries' progress.

This paper focuses on the Emerging Innovators group in 2025 [2] - Bulgaria, Hungary, Latvia, Poland, Romania, and Slovakia. Finally, our attention turns to Romania, whose

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innovation policies align with the European trend [3][4][5][6]. Within the Emerging Innovators' group, Romania stands out as a case of strong relative progress but persistent structural gaps [7][8][9][10]. By analyzing the evolution of the Summary Innovation Index (SII) [1], performance changes, annual gaps, and Compound Annual Growth Rates (CAGR) [11], with a particular comparison to Croatia and the EU27 average, we aim to highlight Romania's trajectory, strengths, and limitations.

In recent years, we have carried out a series of analyses on innovation at the EU level and we have highlighted the strong relationships between innovation and ICT. Given the complexity of the two entities, innovation and ICT, we employed a variety of indicators to capture their multiple dimensions. For ICT we have used:

- Network Readiness Index (NRI), originally part of the World Economic Forum's *Global Information Technology Report*, nowadays published by the Portulans Institute in partnership with the University of Oxford's Saïd Business School. The results of our research were published in [12][13].
- Human Resources in Science and Technology (HRST) Index published by Eurostat. The results of our research were published in [12][14].
- Gross Domestic Expenditure on R&D (GERD), both published by Eurostat. The results of our research were published in [14].
- ICT Development Index (IDI), a composite index calculated annually since 2009 by the International Telecommunication Union and published in the *Measuring the Information Society Report (MISR)*. The results of our research were published in [15].

The stage of innovation across European countries has been captured through several indicators such as the Summary Innovation Index (SII) and Global Innovation Index (GII) [13][16]

In addition, in our work, we aimed to identify and analyze good practice models, such as Estonia [12], which has achieved outstanding results in innovation, or Bulgaria, an Emerging Innovator that has also recorded solid progress in innovation [14][17]. These examples may serve as valuable benchmarks for Romania in its efforts to improve its position within European innovation rankings.

2. The European Innovation Scoreboard (EIS)

The European Innovation Scoreboard (EIS) is a European Commission initiative that provides "*a comparative analysis of innovation performance of the European Union (EU), the 27 Member States, 12 neighboring European countries, and 11 global competitors*" [1]. The report is published annually and has now reached its 25th edition. It offers an overview of the state of innovation for the economies mentioned above.

Innovation performance is measured through a set of sub-indicators whose structure and calculation methods are subject to continuous refinement in order to better reflect the EU's evolving needs and priorities. The 2025 edition, once again redesigned compared to the 2021–2024 period, includes 32 indicators, divided into four main categories and 12 dimensions. Based on these 32 equally weighted indicators, a country-level composite index is calculated, known as the **Summary Innovation Index (SII)**.

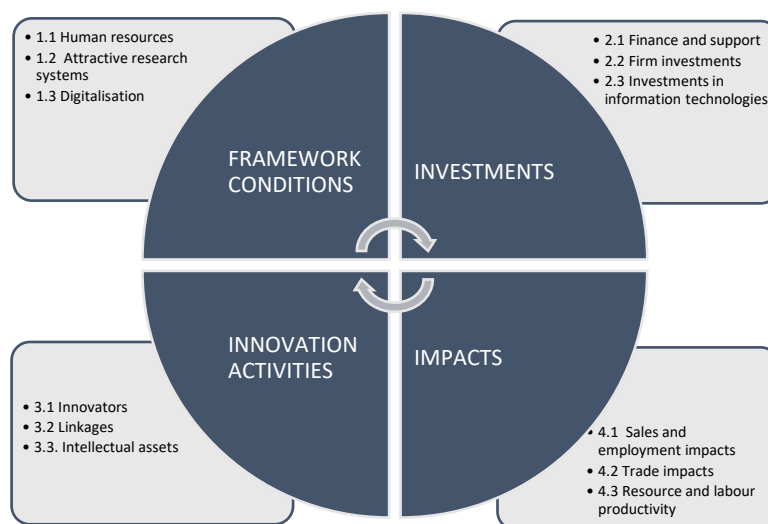


Figure 1. The structure of the Summary Innovation Index (SII) in 2025

(chart made with Ms. Excel, by authors)

Based on their SII in 2025, the EU27 Member States are categorised into four different groups:

- Innovation Leaders are Member States with performance above 125% of the EU average in 2025: Sweden, Denmark, the Netherlands and Finland.
- Strong Innovators are Member States with a performance between 100% and 125% of the EU average in 2025: Ireland, Belgium, Luxembourg, Austria, Germany, France, and Estonia.
- Moderate Innovators are Member States with performance between 70% and 100% of the EU average in 2025: Malta, Slovenia, Italy, Spain, Portugal, Cyprus, Lithuania, Czechia, Greece and Croatia.
- Emerging Innovators are Member States that have a performance level below 70% of the EU average in 2025: Hungary, Poland, Slovakia, Latvia, Bulgaria, and Romania.

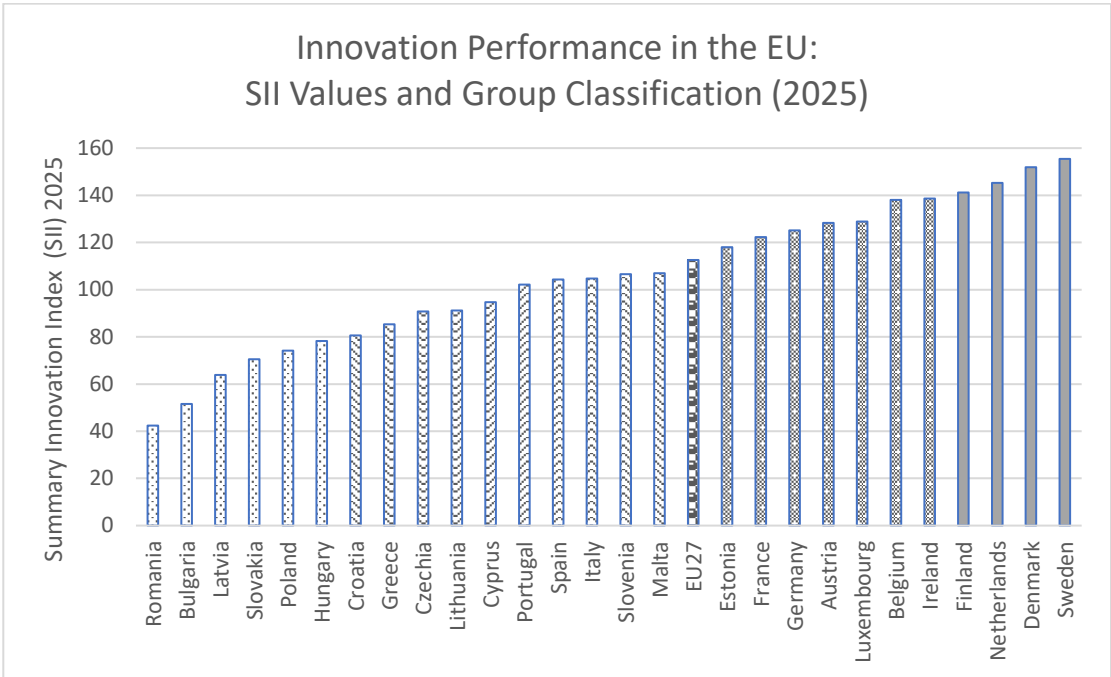


Figure 2. Innovation Performance in the EU: SII Values and Group Classification (2025). The countries are ranked by order of performance, increasing, from left to right.

3. Innovation in the Emerging Innovators Group: descriptive analysis with focus on Romania, in the period 2018–2025

3.1. Materials and methods

For the materials and methodology, all tables, charts and graphics included in this paper were created by the authors using Microsoft Excel, with data sourced from the European Innovation Scoreboard (EIS) 2025, through the EIS Interactive Tool [1][2].

Data: SII values and 23 sub-indicators, for the 27 European Member States, in the period 2018-2025. According to [1]:

- the values are indexed to the EU27 in 2018;
- 0-values means that the country had the lowest performance for that indicator, or was identified as a negative outlier and rescaled to 0 during the rescaling phase.

In order to depict the evolution (growth or decline) of an indicator, we use the Compound Annual Growth Rate (CAGR) measure [11]. While annual fluctuations may occur, CAGR provides a synthetic indicator of long-term progress by smoothing out short-term variations. The CAGR for a country/economy is computed using the formula:

$$\text{CAGR}(t_0, t_n) = (V(t_n) / V(t_0))^{1/(\text{number of periods})} - 1$$

For all indicators and sub-indicators, the analysis covers 2018–2025 (7 periods), except for the ‘Innovators’ sub-indicator (3.1), which spans 2021–2025 (4 periods).

The performance change over a period was computed with the formula:

$$\text{Performance} = \text{Value\_last\_year} - \text{Value\_initial\_year}$$

The annual performance change in year i is computed as the difference between the value in year i and the value in year $i-1$.

3.2. Comparative Analysis of Innovation Performance

According to the European Innovation Scoreboard classifications in 2025, the Emerging Innovators are: Bulgaria, Hungary, Latvia, Poland, Romania, and Slovakia. Again, according the EIS 2025, these 6 countries have consistently been part of the Emerging Innovators group throughout the entire period covered by this analysis, 2018-2025.

Some other countries *graduated* to Moderate Innovators group: in 2018 Greece was classified as an Emerging Innovator; starting from 2019, it moved into the Moderate Innovators group and has remained there since. Similarly, Croatia was part of the Emerging group until 2022, but advanced to the Moderate Innovators group in 2023, where it has also remained. [1]

We have to mention that the previous two statements are based on the EIS 2025. Over time, indicators change, and values change also, yielding to changes in past classifications. For instance, in EIS 2024, Hungary and Croatia were at the limit between Moderate and Emerging Innovator, with Croatia classified as an Emerging Innovator, while Hungary as a Moderate Innovator. In EIS 2025, their rankings reversed.

In the next part of the analysis, we focus on the evolution of innovation among the Emerging Innovators, with particular attention to Romania in comparison with Croatia, which is considered a ‘best-practice’ case.

For the six Emerging Innovators, overall progress was observed over the 2018–2025 period. In the following study case, the countries are ordered by the 2025 innovation performance.

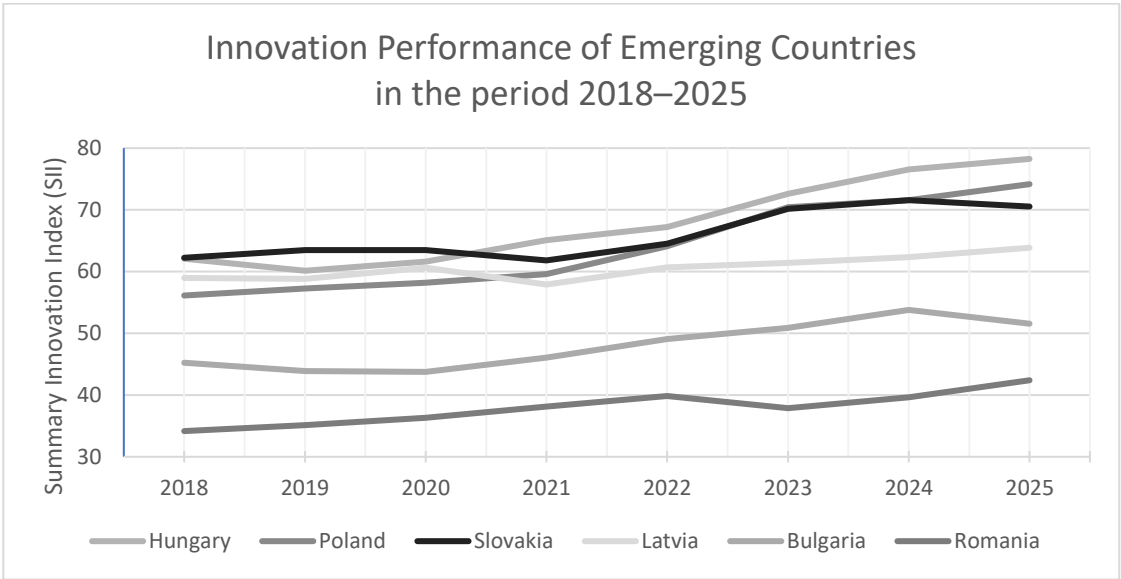


Figure 3. Innovation Performance of Emerging Countries in the period 2018–2025. The countries are ranked by their SII 2025 performance, with Hungary on the left as the most innovative within the group.

Romania shows steady advancement, except for the setback recorded in 2023. In terms of innovation, Romania occupies the most modest position, according to the country’s profile published within EIS 2025. It performs at 37.7% of the EU27 average in 2025, while the Emerging Innovators group performs at 56.4% of EU27.

However, despite Romania’s relatively low position, a remarkable progress can be observed in the current year: Romania recorded the best performance improvement in 2025 compared to the previous year, within its performance group, significantly higher than that of its Emerging Innovator peers and the overall EU27 average, as illustrated in the table below.

Table 1. Performance change for the Emerging Innovators

Measure	EU2						
	7	HU	PL	SK	LV	BG	RO
Performance Change 2025 vs 2018		16.1	18.0		4.9		8.2
	12.59	8	4	8.30	0	6.32	3
Performance Change 2025 vs 2024				-	1.5	-	2.7
	-0.44	1.71	2.58	1.05	4	2.23	3

					1.1		3.1
Compound Annual Growth Rate	1.71	3.36	4.06	1.81	5	1.89	3

The Compound Annual Growth Rate (CAGR) also demonstrates Romania’s progress over the past seven years, which is well above the EU27 average and places Romania in the top half of the Emerging Innovators group, alongside Poland and Hungary.

In fact, Romania recorded in 2025 the highest annual performance change across the entire period under analysis, of almost 3%, consolidating its position:

Table 2. Annual performance change for Romania in the period 2019-2025

2019	2020	2021	2022	2023	2024	2025
0.98	1.17	1.83	1.70	-1.95	1.77	2.73

In spite of Romania’s progress over the past year, the gap between Romania and the EU27 continues to widen. In the next study case, we compared the evolution of Romania vs. EU27 vs. Croatia (the values are indexed to EU27 in 2018):

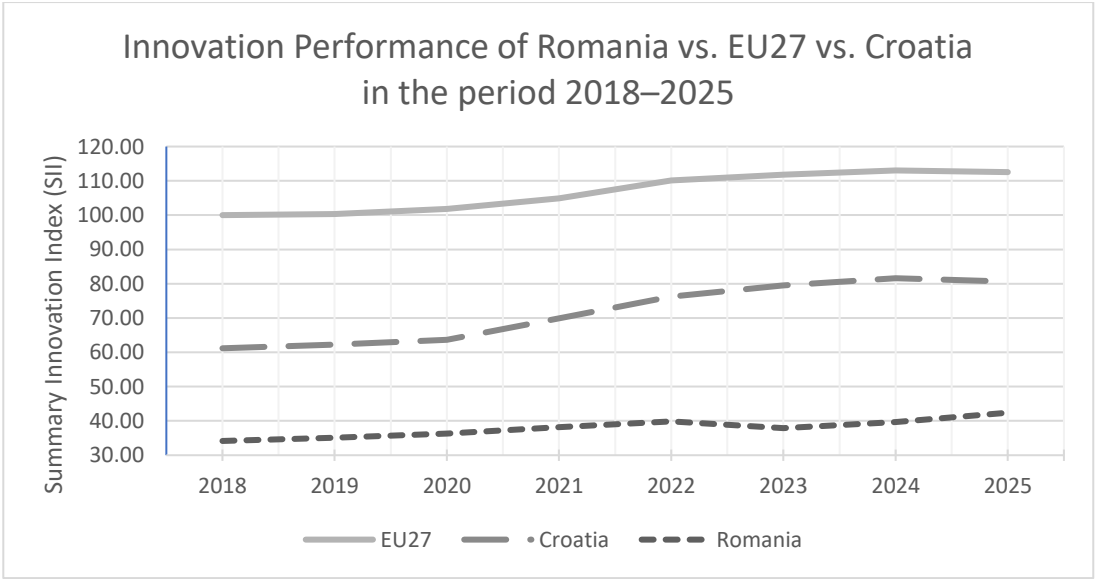


Figure 4. Innovation Performance of Romania vs. EU27 vs. Croatia in the period 2018–2025. The economies are ranked by their SII 2025 performance, with EU27 on the left as the most innovative.

Croatia experienced a significant increase in innovation performance between 2018 and 2025, reducing constantly the gap with the EU average and enabled the country to advance into the group of Moderate Innovators from Emerging in 2022.

Table 3. Annual innovation performance gap between Romania, the EU27 average, and Croatia in the period 2018–2025

	2018	2019	2020	2021	2022	2023	2024	2025	Resolution
Gap Romania vs. EU27	65.84	65.23	65.49	66.8 0	70.2 9	73.9 1	73.3 7	70.2 0	diverged
Gap Croatia vs. EU27	38.82	38.10	38.16	35.0 2	33.8 9	32.3 1	31.4 3	31.9 8	converged

In Romania’s case, the gap with respect to EU27 increased from 65.84% in 2018 to 70.20% in 2025.

To capture the average yearly growth, we use the Compound Annual Growth Rate:

Table 4. The Compound Annual Growth Rate (CAGR) indicator for the 3 economies

Economy	EU27	Croatia	Romania
CAGR	1.71	4.02	3.13

Table 4 shows that both Croatia and Romania are well above the EU27 average: EU27 has grown, in average, with 1.71% yearly, while for Croatia and Romania the average yearly growth percentage is 4.02%, respectively 3.13%. However, in Romania’s case, the relatively low starting values result in slow overall progress. Between 2018 and 2025, Romania’s performance increased by only 8.23 points, compared with 12.59 points for the EU27 (see Table 1), thereby widening the gap between the two economies. (Both performance change values are reported relative to the same baseline: EU27 in 2018).

3.3. Decomposing Innovation: Sub-Pillar Analysis

As we observed above, although Romania has made substantial progress in recent years, the gap with the EU27 average and other countries remains concerning. In this section, we

aim to perform a structural analysis of innovation evolution, by examining the changes in sub-indicators for the three economies: Romania, the EU27, and Croatia.

Thus, we aim to identify which sub-indicators best explain the observed differences and which of them hold back Romania's transition.

To capture long-term performance dynamics, we computed the CAGR values for each of the three economies and for each of the 32 sub-pillars. The results are presented below.

Table 5. The Compound Annual Growth Rate (CAGR) and resolution for each innovation pillar for Romania, the EU27 average, and Croatia in the period 2018–2025

No	Indicator	CAGR Romania	CAGR EU27	CAGR Croatia	Romania vs. EU27	Romania vs. Croatia
	Summary Innovation Index (SII) 2025	3.13	1.71	4.02	+	-
1.1	Human resources	0.09	0.94	3.16	-	-
1.2	Attractive research systems	11.92	1.76	4.24	+	+
1.3	Digitalisation	5.79	5.26	2.63	+	+
2.1	Finance and support	-6.16	1.79	14.71	-	-
2.2	Firm investments	-0.53	0.16	3.97	-	-
2.3	Investments in information technologies	9.67	8.04	9.30	+	+
3.1	Innovators	-16.67	2.11	-1.16	-	-
3.2	Linkages	-5.81	4.48	5.91	-	-
3.3	Intellectual assets	1.96	-2.63	3.86	+	-
4.1	Sales and employment impacts	-3.66	0.21	1.20	-	-
4.2	Trade impacts	0.93	1.79	-0.38	-	+

4.3	Resource and labour productivity	7.96	1.79	4.53	+	+

The ‘+’ symbol indicates an increase in innovation performance for Romania, while the ‘–’ symbol denotes a decline.

As we can see in the table above, Romania have had a better progress rate than the average EU27, and lower than Croatia, at global innovation level. This evolution was largely analyzed in the previous section.

On sub-pillow level, compared with EU27 average and Croatia, the strengths of Romania are:

- Attractive research systems
- Digitalisation
- Investments in information technologies
- Resource and labour productivity

Among the weaknesses, we can list:

- Human resources
- Finance and support
- Firm investments
- Innovators
- Linkages
- Sales and employment impacts

While several strengths can be observed, structural weaknesses persist, limiting Romania’s capacity to close the gap. Strengthening Romania’s weaker sub-pillars through targeted measures is crucial.

4. Conclusions

Our analysis shows that Romania has achieved significant progress in innovation between 2018 and 2025, outperforming the EU27 average in terms of growth dynamics and positioning itself among the top Emerging Innovators alongside Poland and Hungary. However, due to its initially low baseline, Romania’s absolute performance remains modest, and the gap with both the EU27 average and Croatia has widened. The sub-pillar analysis reveals important strengths - notably in research systems, digitalization, IT investments, and productivity - but also persistent weaknesses in human resources,

financing, firm investments, and innovation linkages. These structural challenges underline the need for targeted policy interventions to reinforce Romania's weaker dimensions and accelerate its convergence within the European innovation landscape.

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DIGITIZATION AND THE USE OF ARTIFICIAL INTELLIGENCE IN EDUCATION AND THE LABOR MARKET IN ROMANIA

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Abstract

This article attempts to analyze current trends in digitization as well as the use of artificial intelligence (AI) in education, with a focus on the higher education system in Romania. The present study synthesizes recent literature, European and international policies, and national strategic programs, providing practical examples of how new digital technologies are being integrated into teaching and assessment by faculty. Opportunities for student learning are also discussed, as well as the streamlining of administrative processes, the development of digital skills, and associated risks such as ethical concerns, data security, algorithmic bias, and dependence on external providers. The final part of the article includes illustrative tables and graphs regarding the evolution of digitization in educational institutions, as well as a comparative study between international best practices and the current Romanian context. Finally, the article proposes a series of public policy recommendations and university practices suitable for a responsible and sustainable implementation of AI in the Romanian academic environment for both students and faculty.

Keywords: digitization; artificial intelligence; education; higher education; public policy; digital skills.

JEL Classification: I21; I28; J24; O33.

1. Introduction

The new trends in the digitization of education, as well as the integration of artificial intelligence (AI)-based tools, represent one of the most significant changes in the past five years, marking structural transformations in the contemporary Romanian education system.

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The COVID-19 pandemic has accelerated, over the past years, the adoption of new digital technologies and has highlighted both the potential and the limitations of the current educational systems in Romania. In this context, universities face the question of how they can leverage AI to further improve the quality of education without jeopardizing it in the long term, while promoting inclusion and adequately preparing students for a labor market that is continuously evolving. Artificial intelligence (AI) involves the use of digital technology to create and implement systems that can ultimately perform tasks with human intervention. AI has the capability to closely mimic human thinking, but its greatest advantage lies in processing information at a faster and more precise pace, significantly reducing the time required for learning processes, information synthesis, and data processing.

2. Theoretical Framework of Specialized Literature

Specialized literature highlights several major directions in which AI influences education: personalization of the learning process through adaptive systems; assessment by faculty and real-time feedback by students; decision support for teachers and institutional management tailored to each educational institution; and long-term predictive analysis to prevent school dropout in Romania. Existing international organizations, such as UNESCO and OECD, have published a series of guidelines and analyses emphasizing the importance of developing educational policies that combine technological innovation with the protection of students' rights.

Advantages of AI use:

- Continuous personalization and adaptability of the learning process.
- Administrative efficiency and decision support for involved stakeholders.
- Access to an extensive resource base and distance learning opportunities.

Limitations and risks of AI use:

- Ethical issues that may arise related to transparency, fairness, and accountability.
- Data protection and user information security.
- Dependence on external technology providers and the risk of “vendor lock-in”.
- The need for continuous training of teachers and students to use digital tools effectively in Romanian educational institutions (UNESCO, 2021; OECD, 2021).

2.1. Educational Policies and Strategies at International and National Levels

Over time, the European Union has strengthened its priorities for the optimal implementation of digital education through the Digital Education Action Plan 2021–2027, which aims to develop digital skills among teachers and students, provide adequate infrastructure, and ensure digital inclusion for each EU member state.

At the international level, UNESCO has also published a series of guidelines for decision-makers regarding the responsible use of AI in education, emphasizing the need for an approach centered on ethical principles, transparency, and user data protection. In Romania, the SMART.Edu Strategy for the period 2021–2027 proposes a framework for modernizing the Romanian educational system, including sustainable long-term investments in IT

infrastructure, digital resources, and teacher training to ensure the digital competencies necessary for effective use in the educational process.

This article used a mixed methodology: a review of specialized literature and documents published between 2018–2025; a comparative analysis of best practices reported in international organizations' documents worldwide; and illustrations through tables and graphs showing future trends for higher education institutions. The data used in the graphs are demonstrative; for detailed empirical analyses, official data from institutions such as the National Institute of Statistics (INS), the Ministry of Education, EUROSTAT, and OECD were consulted.

2.2. The Impact of AI on Teaching and Continuous Learning

Current adaptive learning systems use a series of algorithms to adjust the learning pace

It is also important to provide support for faculty from educational institutions, which requires, and the content delivered to students based on their individual performance and learning style. Normally, this can lead to increased long-term engagement and significant improvement in academic outcomes; however, their effectiveness depends on the quality of the data provided by each instructor, as well as on the pedagogical design of the learning systems.

Assessment by specialized faculty and feedback AI enables automated evaluation of knowledge tests in an objective manner, as well as the provision of immediate feedback to students. For qualitative assignments given in seminars or courses (essays, projects), advances in natural language processing (NLP) allow semi-automated assessments, provided they are validated to avoid interpretation errors by students.

Several AI-based tools can offer pedagogical recommendations, detect students at risk of attention deficits, and optimize the planning of available resources. Importantly, the teacher's role remains central; AI has a complementary function worldwide, assisting in synthesizing and structuring information to facilitate the teaching and learning process.

2.3. Advantages and Limitations of AI Use in the Educational System

Digitization in education includes the use of online platforms by institutions, open educational resources (OERs), collaboration tools, and AI-based applications. These innovative technologies transform the way teachers teach, enable continuous learning, and allow periodic assessment of students, while also personalizing the current educational process.

Advantages of AI use:

- Continuous personalization and adaptability of the learning process.
- Administrative efficiency and decision support for involved stakeholders.
- Access to an extensive resource base and distance learning opportunities.

Limitations and risks of AI use:

- Ethical issues that may arise related to transparency, fairness, and accountability.
- Data protection and user information security.
- Dependence on external technology providers and the risk of “vendor lock-in”;
- The need for continuous training of teachers and students to use digital tools effectively in Romanian educational institutions.

For students, AI implementation in education offers several advantages, including:

- Rapid access to information and educational resources in real time.
- Flexible learning, whether remote or hybrid on campus.
- Adaptive assessment through periodic digital tests and simulations.
- Development of digital skills and critical thinking.

For teachers, there are also several challenges regarding AI use and its integration into the educational system:

- The need for short-term retraining in digital technology use.
- Creation of interactive materials and engaging educational platforms for each subject.
- periodic monitoring (semester-based) of student progress through data analyses (Learning Analytics) for each subject.

All these aspects also come with a series of advantages for both students and teachers. Among the main advantages analyzed, we can highlight:

- Personalization and adaptation of the educational process by each participant in the teaching activity.
- Equal access for all students from different geographic areas, whether urban or rural, with favorable infrastructure.
- Improved motivation for both teachers and active engagement from students.

At the same time, these advantages and disadvantages bring a set of challenges for all beneficiaries regarding the long-term use of AI in education. Among the most relevant challenges identified in this article's research are:

- Inequalities in access to technology and the internet are due to differences in urban and rural infrastructure.
- Dependence on digital platforms and AI over time may lead to functional illiteracy for some users.
- User data security and privacy issues.
- The need for a clearly implemented legislative and ethical framework at both the European Union and international levels.

2.4. Official Data and Statistics on Education Digitization

To complement the analysis, this section integrates real data from official sources (EUROSTAT, Digital Skills & Jobs Platform, national reports). These provide a clearer picture of the level of digital skills and the use of online resources in Romania compared to the European Union average.

Europe's growth and well-being heavily depend on how we utilize data and connected technologies. AI has the potential to radically change our lives, for better or worse.

Therefore, in June 2024, the European Parliament adopted the Artificial Intelligence Act, the world's first comprehensive set of rules for safe AI systems that respect fundamental rights.⁴

In EU countries, the digital industry and business-to-business (B2B) applications are highly developed. With high-quality digital infrastructure and a regulatory framework that protects

⁴ Artificial Intelligence: Opportunities and Risks (2020), European Parliament Report. Accessed 07-10-2025

privacy and freedom of expression, the EU could become a global leader in the data economy.⁵⁶

Thanks to AI, citizens could benefit from: improved healthcare services, safer vehicles and transport systems, and products and services that are more affordable, sustainable, and tailored to their needs. AI also facilitates access to information, education, and training. AI can also enhance workplace safety, as robots can perform dangerous tasks in certain fields, and can lead to the emergence of new professions as AI-based industries grow and continuously evolve.⁷

Year	Digital Platforms %	Artificial Intelligence (%)
2018	20	10
2019	30	15
2020	40	22
2021	60	40
2022	70	55
2023	78	63

Table 1. Adoption Rate of Digital Platforms and AI Tools in Higher Education Institutions (percentage of institutions)⁸

Eurostat conducted several studies in 2023 regarding AI use in higher education institutions across the European Union and observed that, since 2021, there has been a year-on-year increase in the use of digital platforms and AI by students and faculty in universities.

This growth in the use of digital platforms and access to AI by students and faculty was also influenced by the COVID-19 pandemic, which necessitated distance learning—online from home or eLearning. Ultimately, online instruction offers a series of advantages: facilitating access to study from anywhere in the world, regardless of internet connection quality or physical distance.

Table 1 presents the adoption of digital platforms and AI tools within higher education institutions across the European Union. The data, provided by Eurostat (2024), indicates a steady increase in the use of online learning systems and AI-driven applications since 2021. This trend reflects both students' and faculty members' growing reliance on digital technologies in the academic environment.

A key factor contributing to this increase was the COVID-19 pandemic, which accelerated the transition to online learning and eLearning systems. Universities were compelled to implement remote teaching solutions, leading to wider exposure to digital platforms and AI-based educational tools.

The figure demonstrates that digital adoption is not merely a temporary response to a crisis, but rather an evolving structural trend. The gradual normalization of digital platforms

⁵ Idem

⁷ Artificial Intelligence: Opportunities and Risks (2020), European Parliament Report. Accessed 07-10-2025

⁸ Eurostat, Online Learning Statistics (2024). Accessed 08-10-2025

suggests a permanent transformation in the way education is delivered and consumed, fostering flexible access to learning resources, improving inclusivity, and supporting the development of digital skills among both faculty and students.

Year	Initial Training (%)	Continuous Training (%)	LMS use (%)
2018	25	10	30
2019	30	12	35
2020	45	25	60
2021	55	40	70
2022	60	50	75
2023	65	55	78
2024	68	60	80

Table 2. Illustrative Data on Faculty Digital Skills (percentage).⁹

Table 2 also illustrates the progressive improvement in faculty digital skills over the years, reflecting both initial and ongoing training, as well as increased use of Learning Management Systems (LMS).

Table 2 provides illustrative data regarding the evolution of faculty digital skills between 2018 and 2024, focusing on three main indicators: initial training, continuous training, and the use of Learning Management Systems (LMS). The data are sourced from Eurostat (2023), the Brio Report (2022), and the Digital Skills & Jobs Platform (2024).

The table reveal a clear upward trajectory in all three categories. Initial training increased from 25% in 2018 to 68% in 2024, highlighting the growing emphasis on integrating digital competencies into teacher preparation programs. Continuous training also saw a substantial rise, from only 10% in 2018 to 60% in 2024, reflecting the need for lifelong professional development in digital literacy. Similarly, LMS use expanded from 30% in 2018 to 80% in 2024, indicating that online learning platforms have become an essential component of modern teaching practices.

These findings suggest that faculty members are progressively more equipped with digital skills, both through structured training and through practical engagement with online platforms. The data underlines the importance of sustained institutional investment in digital infrastructure and professional development programs, which are essential for ensuring the long-term effectiveness and sustainability of digital education strategies.

Year	Average Score %
2018	65

⁹ Eurostat (2023), Brio Report (2022), Digital Skills & Jobs Platform (2024) Accessed 08-10-2025.

2019	66
2020	67
2021	68
2022	69
2023	69.5
2024	70

Table 3. Evolution of Students' Average Performance ¹⁰

Table 3 illustrates the evolution of students' average performance in higher education institutions within the European Union during the period 2018–2024, with a particular focus on the role of online learning (eLearning). According to Eurostat (2024), the data were collected from a representative sample of students actively engaged in digital platforms and online educational resources.

The results clearly show that student performance remained relatively stable prior to 2020, but starting with the COVID-19 pandemic and the transition to remote learning, there was a significant shift. Between 2020 and 2024, a consistent upward trend in academic outcomes can be observed, reflecting both the increased familiarity of students with digital tools and the improvement of institutional eLearning infrastructure.

This evolution highlights not only the adaptability of students to new learning environments, but also the effectiveness of integrating digital platforms and AI-supported resources into the educational process. The findings suggest that, when properly implemented, eLearning can enhance student motivation, provide flexible access to materials, and improve long-term academic performance.

Indicator Analyzed	Romania	EU Average
Basic Digital Skills (ages 16–74)	28%	56%
Participation in Online Courses (2023)	10%	30%
Students with Functional Digital Literacy (Brio, 2022)	25%	n/a

Table 4. Comparative Indicators on Digitalization and Education. Romania vs EU.¹¹

Table 4 highlights a comparative analysis of digitalization and education between Romania and the European Union average, based on three key indicators: basic digital skills among individuals aged 16–74, participation in online courses, and students with functional digital literacy. The data, collected primarily by Eurostat in 2023 and complemented by the Brio Report, reveal notable disparities.

¹⁰ Eurostat, Online learning statistics (2024). Accessed 08-10-2025

¹¹ Eurostat (2023), Brio Report (2022), Digital Skills & Jobs Platform (2023) Accessed 08-10-2025

For Romania, only **28%** of individuals aged 16–74 report basic digital skills, compared with the EU average of **56%**. This indicates a significant skills gap that places Romania below the European benchmark for digital readiness.

When it comes to participation in online courses, Romania registers just **10%** in 2023, while the EU average reaches **30%**. This suggests limited engagement in structured eLearning activities, which could negatively affect the development of lifelong learning practices and digital adaptability.

The third indicator, functional digital literacy among students, shows that Romania achieved **25%**, though EU-wide data are not available for comparison. This figure reflects structural challenges within the Romanian education system, especially the urban–rural divide, where many students in rural or disadvantaged urban areas face poor or nonexistent internet access due to insufficient infrastructure.

Integrating both theoretical perspectives and empirical observations, the findings indicate that while AI has the potential to significantly transform education, its success depends on several interrelated factors: the quality of educational infrastructure, the digital preparedness of faculty, an adequate legal and institutional framework, and broader social acceptance.

To ensure equitable and sustainable integration of AI in education, higher education institutions should adopt a long-term strategy combining technological innovation with ethical principles and coherent public policies. Recommended institutional measures include:

- Developing clear institutional policies on the use of AI in teaching and assessment, including ethical guidelines and data protection protocols.
- Investing in faculty training for both digital competencies and digital pedagogy.
- Promoting pilot projects and national/international collaborations to exchange ideas and best practices.
- Ensuring transparency and conducting regular evaluations of AI tools to identify errors and methodological limitations.
- Actively involving students in decision-making processes concerning the selection and implementation of digital tools used in courses, seminars, and institutional assessments.

3. Impact of AI on Changes in the Labor Market

The labor market in Romania is in a state of continuous transition and adaptation, largely driven by digitalization. Since 2020, the labor market has been constantly subjected to rapid and unpredictable changes, forcing employers and entrepreneurs to adapt at an accelerated pace to these new transitions.

New workplace technologies, particularly automation, are reshaping skill requirements and the way employees perform tasks across various sectors.

Jobs affected by AI that are disappearing and new professions emerging:

- Repetitive and routine jobs (e.g., commercial operators, supermarket cashiers) are being replaced by robots and AI systems.
- New professions are emerging data analysts, AI specialists, cybersecurity and data protection consultants, digital platform managers.

- The need for reskilling and continuous learning has become essential for maintaining employment.

The implementation of AI in the labor market also brings several advantages:

- Increased labor productivity for both employers and employees.
- Opportunities for remote work and greater flexibility in work schedules.
- Reduced production costs and optimization of learning and knowledge acquisition processes in real time.
- Access to higher-paying jobs for employees with digital skills that meet employer requirements.
- New Career Opportunities in the Digital Sector

At the same time, the use of AI in the labor market also brings certain disadvantages and risks:

- Increasing the technological gap between urban and rural areas.
- SMEs in the public sector adopt AI more slowly compared to large corporations or multinational companies.
- Loss of traditional jobs in certain production and transport sectors.
- Rising technological unemployment among workers with limited skills.
- Growing professional inequalities between highly skilled employees (with higher or secondary education) and unskilled workers.
- Pressure to increase wages in certain sectors.
- Automated decision-making may lead to workplace discrimination or excessive monitoring.

In addition, AI adoption can alter the balance of power between employers and employees in specific sectors:

- Technological automation reduces the employer's dependency on human labor over time.
- Certain professional roles associated with traditional employment may become obsolete.
- There is a need for adequate social policies to protect vulnerable workers across different sectors.

AI's impact on the Romanian labor market has led to significant changes, particularly affecting jobs in production and manufacturing (line workers, quality control), transport and logistics (drivers, manual handling), as well as retail and repetitive administrative services.

According to statistics, Romania ranks last in the EU in terms of AI implementation within companies. Current estimates indicate that up to 30% of certain jobs could be fully automated by AI by 2035. This trend is driven by digitalization and the urgent prioritization of process automation.¹²

In 2023, Romania recorded a threefold increase in the number of foreign workers compared to 2019, exceeding 84,000 active foreign employees. The same year also saw the highest number of permanent departures of Romanians, with over 700,000 people leaving the

¹² Badea, Bogdan. "How the Labor Market Evolved in 2024 and What to Expect in 2025," article published in *Review & Trends* by eJobs, 2024. Accessed 09-10-2025

country. These figures confirm a clear trend: local labor markets are transforming into a single, skills-driven market where recruitment is based not on proximity but on competencies and specific needs.¹³

In the coming years, AI is expected to advance across numerous sectors, and humanity must become aware of its impact on everyday life and learn to interact with it consciously and constructively.

Global companies are increasingly investing in AI technologies, with remarkable results across various sectors: industrial production, transport, infrastructure, financial services, healthcare, digital marketing, commerce, and education.

The labor market remains a dynamic space where human potential and machine capabilities merge into entirely new structures for the future. This evolution is already underway, offering opportunities to explore innovative ways of working, collaborating, and innovating.

AI is not merely a trend, but a global force that will continue to redefine productivity, efficiency, and added value across almost every sector of activity.¹⁴

4. Conclusions

Looking ahead, Romania has the chance to use digitalization and artificial intelligence (AI) to strengthen its education system and increase the competitiveness of its labor market within the European Union. To make this happen, it is important to create a national program for digitalization and AI, with clear short, medium and long-term goals. Such a program should focus on building infrastructure, continuous training for teachers and students, and monitoring results.

Digital inclusion should be a top priority for Romania soon. High-speed internet, digital devices, and access to online learning resources need to be available equally for students in both urban and rural areas. Closing this gap is essential to ensure that all students benefit from AI-supported education, which can help reduce differences in learning outcomes and open more job opportunities in a labor market that is constantly changing.

Professional development is another key area where Romania still work must do. Training programs should target both teachers and students, with a focus on digital skills, AI literacy, and the ability to use technology effectively in teaching, learning, and professional settings. Collaboration with international institutions can help by sharing knowledge and adopting best practices.

Ethical and regulatory aspects are also very important when it comes to AI. A clear ethical framework should guide the use of AI in education and at work, ensuring transparency, accountability, and fairness. Protecting personal data, avoiding biased algorithms, and making responsible decisions with AI need to be part of institutional policies.

¹³ Idem

¹⁴ How Artificial Intelligence Is Changing the Labor Market. How It Has Already Done So" (6 February 2025), Profit.ro. <https://www.profit.ro/povesti-cu-profit/cum-schimba-inteligenta-artificiala-piata-muncii-cum-a-facut-o-deja-21924207> Accessed 09-10-2025

Monitoring and evaluation are equally necessary. Universities and companies should regularly assess AI applications to measure their impact on student performance, workforce productivity, and social outcomes. This evidence-based approach can help improve policies and maximize the benefits of AI adoption.

In conclusion, AI and digitalization are not just tools, but strategic factors that can transform Romania into a more competitive and digitally prepared country in the years to come. Responsible, ethical, and sustainable implementation is key to making the most of these opportunities, reducing risks, and ensuring equal access to education and jobs in the digital era. By focusing on infrastructure, digital skills, ethical frameworks, and continuous evaluation, Romania can position itself as an active player in the global digital economy. Digitalization and AI open unprecedented opportunities for the modernization of higher education; however, their full potential can only be realized through responsible implementation, supported by coherent policies, professional training, and adequate infrastructure for each institution. Romania benefits from strategic documents (SMART.Edu) and European support, but it remains necessary to translate these strategic directions into concrete, measurable projects at the institutional level.

Over the past five years, digitalization and artificial intelligence (AI) have been key drivers of societal transformations. Education for young people, labor market changes, and the economic environment are the sectors most influenced by these rapid developments across various domains. Romania must invest in the long term to keep pace with other European Union member states in continuous development of digital competencies among users, reducing infrastructure gaps between urban and rural areas, implementing social policies for employees affected by automation and at risk of technological unemployment, as well as adopting ethical solutions for the protection and safe use of personal data on AI platforms.

Digital technologies enable innovation, efficiency, and increased productivity at both the company and employee level, but they also bring major challenges concerning personal data security, inequality among employees, and the preparedness of the workforce across different sectors.

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TRENDS RESEARCH TOPICS IN THE ERA OF DIGITALISATION - A BIBLIOMETRIC ANALYSIS OF ACCOUNTING

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Abstract

The use of digitalization and its impact on the accounting field is a subject that has received particular attention in recent academic literature. Unlike prior broader bibliometric analysis, this study uniquely employs a highly focused, real time bibliometric analysis from 2020-2024 to capture the dynamic, rapid evolution of the intersection between digitalization and sustainability in accounting, offering a novel, real time snapshot of emergent trends. To examine the emerging trends in accounting research, this study extracted 1,603 documents published during 2020-2024 in the Scopus database. This study analyzes the number of publications per year, top academic journals, citation metrics of leading academic journals, author impact, leading countries in research, co-occurrence keywords, and trending topics. The findings reveal that research in accounting is incorporating increasingly digital innovations like AI, automation, and big data in aim to improve sustainable reporting. Leading countries in research output are the USA, China, and Italy. The top academic journals that researchers can use as a primary source to conduct a literature review are the Journal of Cleaner Production and Cogent Business and Management. The most cited authors are Zhang Y, Liu Y, and Bekun FV, based on their citation metrics. The co-occurrence analysis highlights that AI, blockchain, and big data play a crucial role in enforcing sustainable practices. Trend topics analysis emphasizes a shift in the focus of the research topics, from cost analysis and risk management to sustainable reporting driven by AI tools and carbon emissions tracking. Future research should examine the integration of AI in sustainable accounting

Keywords: Digitalization of accounting, sustainable, sustainability, Bibliometric analysis, Research trends

JEL Classification: M41

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1. Introduction

As we are living in the digital era, the digitalisation has become an integral part of our everyday life, by affecting all industries, including accounting, finance, and the related fields [1]. The use of digitalisation and its impact on the accounting field is a subject that has received particular attention in recent academic literature [11]. Shifting from industry 4.0 to Industry 5.0 led to a more human-oriented technology. The existing literature focuses mainly on specific aspects of digitalisation in accounting, such as blockchain, artificial intelligence (AI), and automation, without giving a general view of the connection between them and their impact on sustainability of accounting. This study aims to bridge this gap by employing a bibliometric analysis of the recent research related to digitalisation and sustainability in the accounting. By analysing trends in accounting research, this paper identifies the most discussed topics in digital accounting and sustainability, guiding researchers into their future research. The study covers a 5-year period. Starting with a description of the key terms and database used for analysis, it continues with the results, including the number of publications, leading countries in research, most cited articles and authors, the most used keywords and the trend topics in accounting research.

The structure of the paper is organized as follows. The first section covers a comprehensive literature review regarding digitalization of accounting in relation to sustainability. The following section describes the methodology employed, such as bibliometric analysis method, searching criteria and selection of the database. The analyses continue with the result, that covers key findings. The fourth section summarizes the main findings in the research paper and conclusions. The last section covers limitations of the study and directions for further research.

2. Literature review

The term “bibliometric” was first introduced by Paul Otlet in 1934, defining this term as “the measurement of all aspects related to the publication and reading of books and documents” [3], while the term “bibliometrics” was first used by Alan Pritchard, in 1969 [4]. In recent years, we have seen an increase in the use of bibliometric analysis as a tool to conduct scientific research in various fields, thus turning the use of this technique into a trend [5]. Bibliometric analysis is a method for conducting systematic studies of scientific literature to identify trends in a certain field, which is receiving more and more attention with the increasing use of AI [6]. Bibliometric analysis is now used to examine the characteristics, structure, relationships, patterns, current and future trends of scientific disciplines [7].

The process of incorporating the Environmental, Social, and Governance (ESGs) into financial reporting and decision-making is generally referred to as sustainability accounting. Sustainability accounting is a key factor that can influence the way stakeholders

act [8]. More recently, sustainability accounting and reporting is becoming more a matter of mandatory requirements and compliancy, hence causing an expected rise in scientific discussions and publications. Given that sustainability has become a major research stream in recent years, accountants are realizing that their role has shifted from simply preparing financial statements and disclosures to incorporating issues such as emissions tracking, climate risk assessment, and sustainability disclosures into their reporting processes [9]. To be prepared for sustainable reporting, accountants must develop new skills and collaborate with other experts [10]. In their discourse, [11] revealed that digital technologies such as AI, Blockchain, the Internet of Things (IoT), and big data play a crucial role in sustainability practices by supporting ESG reporting, thus fostering economic, social, and environmental sustainability. Often, the digitalization is seen as a useful tool to assist accountants and financial officers while they collect ESG data points and prepare sustainability oriented reports, hence the intersectionality between digitalization and sustainability is given a special focus in our study. In her study, [12] “Accounting digitalisation in the quest for environmental sustainability” highlights that digitalisation of accounting focused on sustainability improves decision-making processes, but integrating them in a proper way is a real challenge. Similarly, [13], reveals that the use of digitalization accounting practices in different industries improves efficiency, transparency, and sustainability, but industries still face significant difficulties in their adoption. Digitalization of accounting is a useful tool to help sustainability accounting through real-time tracking, automation, and alignment with international sustainability standards [14]. To enhance the digitalization of accounting, organizational support is needed to implement digital accounting procedures for accounting professionals [15]. Manufacturing companies can have many advantages by implementing digital sustainable accounting, but this is still a challenge [16]. In his study “Integrating Digital Technologies in Sustainability Accounting and Reporting: Perceptions of Professional Cloud Computing Users”, [17] reveals that Digitalization of sustainability accounting and reporting is a key factor for cloud computing users in the accounting profession. Digital technologies significantly influence sustainability accounting and reporting in the European Union [18]. Digital transformation driven by Industry 5.0 contributes to the potential improvement of sustainability accounting and reporting, with significant links between sustainability and digitization. [19] identifies technological, organizational, and environmental factors that enable or constrain the digitalization of sustainability accounting, reporting, and disclosure. According to his study, there are also organizational constraints, such as the need for technical and training programs, that influence the adoption of new technologies for sustainability reporting.

In their article “Trends and themes in accounting education research: A bibliometric analysis”, [20] concluded that there has been a significant increase in scientific research over the last 30 years, and the most frequently used terms in scientific research are accounting, accounting students, and managerial accounting. They adopt a wide scope in their study and do not necessarily focus on digitalization impact or sustainability issues. Nevertheless, their research reveals that indeed accounting and related fields have gained prominence in research in recent decades.

A research paper that applied the same methodology, the bibliometric analysis, with a focus on the digitalization on accounting was published by [21]. In their paper “Digitalization of Accounting Profession: A Decade of Bibliometric Analysis” they conduct a bibliometric analysis of scientific research on digitalization in accounting for the past 10 years. The results of this paper show that the Journal with the most publications is Business, Management and Accounting, the country with the most publications is the United States, and the most used keyword is Accounting, followed by the terms digitalization and blockchain.

In a very recent study, “Bibliometric Analysis of Digital Financial Reporting: A Comprehensive Review of Research Trends and Emerging Topics,” [22] revealed that there was an increase in research on digitalization in accounting after 2016, peaking in 2023. Moreover, [23] through a bibliometric analysis, by using keyword occurrence analysis found that “big data” and “internet” were the two most frequently used keywords. Meanwhile, [24] found that the most frequently used keywords were “sustainable development”, “environmental management”, and “environmental impact”.

Another study of interest that employs bibliometric analysis, with specific focus on sustainability accounting and reporting have been published by [25]. They conducted a bibliometric analysis to examine the development of sustainability reporting as a research topic and found that the Journal of Cleaner Production ranked first in terms of the number of publications dealing with sustainability - related issues.

3. Methodology

The main objective of this paper is to analyze the trends, growth rate, frequency, and thematic focus of scientific research and publication oriented towards the impact of digitalization on accounting, finance, and auditing disciplines over the last five years, through the assessment of the interconnection between digitalization of accounting and sustainability.

To achieve this objective, the following research questions are raised:

RQ1: Which is the main focus of research when it comes to both digitalization of accounting and sustainability? Is there a connection/intersectionality dimension between digitalization and sustainability reporting?

RQ2: Which are the highest-ranking journals in terms of publications in digitalization of accounting and sustainability and who are the most productive authors in these fields?

RQ3: Are there any prominent countries that lead the research, and which are the countries/regions where more should be done to incentivize the research related to digitalization and sustainable accounting?

RQ4: What is the trend of terms used in conducting a research paper focused on accounting and sustainability and what is the shift in this trend if any?

Database searching

This paper uses a systematic literature review research and bibliometric analysis to examine trends in digital accounting and sustainability research topics. We are especially interested in investigating the intersectionality between digitalization of accounting and sustainability as both these trends have emerged recently and have been discussed broadly under many perspectives.

To conduct the bibliometric analysis, data were obtained from Scopus, as one of the most reliable sources for collecting verifiable data related to academic research. Scopus provides better bibliographic records in terms of accuracy, consistency, control, and relevance of information compared to other search engines [26]. Web of Science, another reliable source for bibliometric analysis, was not used, due to lack of access on behalf of the authors of the study, though the volume of data retrieved from the Scopus database is considered sufficient to guarantee a qualitative analysis and address our research questions

At the time of this study (February 2025), the first integrated reports were prepared fully complying with CSRD (Corporate Sustainability Reporting Directive) and published by the EU companies [27]. Along with similar developments in other developed countries (USA and Southeast Asia) and also considering the boost of digitalization tools, a lot is yet to be learned on how these topics have impacted the practical field and what we learn from the research focus.

Sampling procedures and data collection

To extract relevant data and prepare the initial dataset from Scopus, the search string used is "TITLE-ABS-KEY ("accounting" OR "financial accounting" OR "management accounting" OR "auditing" OR "cost accounting" OR "forensic accounting") AND TITLE-ABS-KEY ("innovation" OR "digital" OR "technology" OR "sustainability" OR "automation" OR "artificial intelligence" OR "blockchain" OR "KPI" OR "key performance indicators"). Hence, we expanded the keywords to include both key terms for digitalization (innovation, digital, automation, artificial intelligence) and sustainability reporting along with necessary context keywords (cost accounting, forensic accounting, auditing, etc.). We used the advanced search option and applied the Boolean search function. To have the most complete and up-to-date picture, the considered data set includes years from 2020 and 2024. To maintain the research relevance, the subject area was restricted to Business, Management and Accounting, and Economics, Econometrics, and Finance. In the document type field, the search was limited to articles in the English language only. No filter was

applied in the countries' search field where the article was published. The query was executed in February 2025. The final dataset included 1,603 documents. The data was downloaded in CSV format, then this file was uploaded to the Biblioshiny app. which was accessed through R Studio for bibliometric analysis. Table 1 shows the workflow diagram of the search strategy and steps followed for data processing.

Phase	Description	Details
Phase 1	Research scope	Using a bibliometric analysis to examine research trends in digital accounting and sustainability
Phase 2	Data sampling	- Data source: Scopus - Time period: 2020-2024 - Language: English - Keywords used: “accounting”, “sustainability”, “AI” - Dataset: 1,603 documents
Phase 3	Software and data processing	- MS. Excel - R studio - Bibliometrixs
Phase 4	Analysis of results and trends	- Growth patterns of research - Contributions by countries and regions - Most productive authors

Table 1. Design methodology workflow³

4. Results

Description	Results
Timespan	2020:2024
Sources (Journals, Books, etc.)	466
Documents	1,603
Annual Growth Rate %	25.4
Document Average Age	2.56
Average citations per doc	15.82
Keywords Plus (ID)	3,743
Author's Keywords (DE)	4,699
Authors	4,669
Authors of single-authored docs	207
Co-Authors per Doc	3.37

³ Elaborated by authors

International co-authorships %	29.76

Table 2: Main information about the documents⁴

Table 2 presents a summary of the bibliometric data analyzed in this paper. There were examined 1,603 documents published between 2020 and 2024, conducted by 4,699 authors. The average number of authors per paper is 3.37 and among them, 207 are authors of single-authored papers, indicating an increase trend of collaboration between researchers worldwide. The average annual growth rate of publication within the timeframe is 25.4%, which shows an increased academic interest in studies that cover topics related to digitalisation and sustainability in accounting. This means that for this period (five years from 2020 to the end of 2024), an average growth rate of 25% has more than doubled the quantity of studies published. The interest is explainable and justified, given the major disruptions and revolutionizing that the digitalization and the sustainability focus has presented for many entities around the world. Approximately, every paper in this data set is cited 15.82 times on average, which is considered a high value considering the data set timeframe.

As illustrated in Table 3, and Figure 1, there is a slight growth of publication trend until 2022, followed by a significant increase of the documents published (75%) between 2023 and 2024, which emphasizes once again the attention that is being given to the use of these topics in the field of research on accounting.

Year	Articles	Percent of growth
2020	222	NA
2021	257	16%
2022	261	2%
2023	314	20%
2024	549	75%

Table 3: Number of articles per year⁵

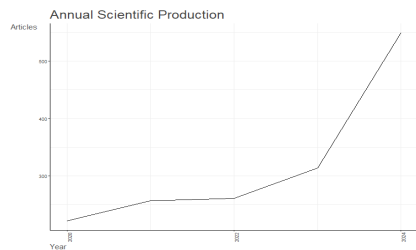


Figure 1: Number of articles produced per year⁶

⁴ Documented by authors. Processed through Biblioshiny using R

⁵ Documented by authors. Processed through Biblioshiny using R

⁶ Documented by authors. Processed through Biblioshiny using R

Figure 2 displays the top academic journals where the majority of the studies in the extracted dataset have been published. Among them, the Journal of Cleaner Production, founded in 1993, is in the top ten sources with 147 papers, and with a considerable difference from the journal in the second place. This can be explained by the high impact factor (9.8) of the Journal of Cleaner Production, which implied a strong reputation making it mostly preferred among researchers worldwide. Following in second place, is Cogent Business and Management Journal, founded in 2014, with 80 publications, with an impact factor of 4.4. In third place is Accounting, Auditing and Accountability Journal, founded in 1988, which is ranked within the top 5 accounting journals, and has an impact factor of 4.8. These 3 journals represent valuable sources for researchers whose research areas are focused in the intersectionality of the digital accounting and sustainability and serve as primary sources of their search and literature review in the field.

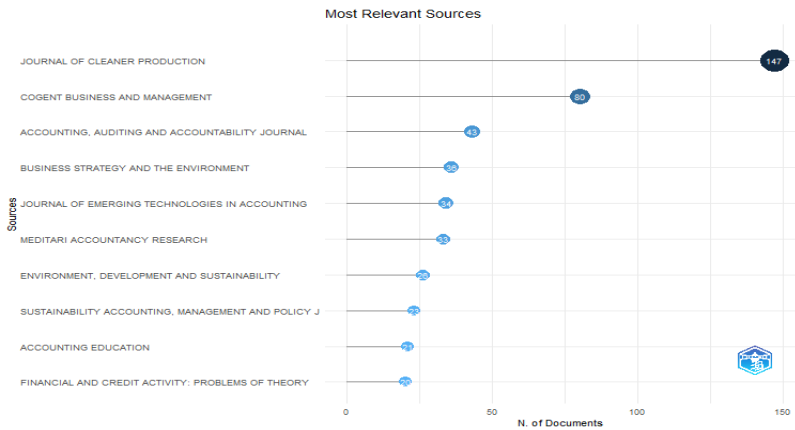


Figure 2: Most Relevant Journals⁷

Table 4 shows the citation metrics of leading academic journals. Among them, the Journal of Cleaner Production has the highest citation metrics, followed by the Accounting, Auditing, and Accountability Journal. The h-index represents the number that a publication is cited at least that number while G- index is introduced by Egghe [28] as an improvement of the h-index of Hirsch to measure the global citation performance of a data set of publications. The m-index is calculated as $h\_index / \text{number of years since the first publication of the paper}$. A higher h-index and g-index show a greater impact and influence of these journals in their respective research areas. Similarly, an m_index greater than 1 indicates that an author has a strong impact over time.

⁷ Documented by authors. Processed through Biblioshiny using R

Journal	h_in dex	g_in dex	m_in dex	Total Citation s	Number of Publications
Journal of Cleaner Production	38	62	6.3	4,677	147
Accounting, Auditing And Accountability Journal	22	35	3.7	1,265	43
Business Strategy and the Environment	17	35	2.8	1,288	36
Journal of Emerging Technologies in Accounting	14	23	2.3	548	34
Sustainability Accounting, Management and Policy Journal	13	22	2.2	528	23
Technological Forecasting and Social Change	13	16	2.2	1,315	16
Resources, Conservation and Recycling	12	19	2.0	412	19
International Journal of Accounting Information Systems	11	17	1.8	587	17
Meditari Accountancy Research	11	17	1.8	324	33
Journal of Information Systems	10	12	1.7	263	12

Table 4: Citation metrics per journal⁸

The local citation impact for authors based on key bibliometric indicators is presented in Table 5. The author who has the highest number of citations is Bekun FV, while author Zhang Y holds the highest h-index, representing a stronger influence.

Therefore, Zhang Y with an h-index of 9, indicate that each of his publications have been cited at least 9 times. Moreover, Zhang Y has also the highest g-index, indicating that his research has received a broader recognition. Wile Bekun FV has the highest number of total citations, Zhang Y's higher h-index and g-index suggest a more consistently cited publicationns, indicating a broader and more sustained influence across multiple publications, which aligns with the definitions of h-index and g-index provided earlier and Liu Y, indicating that not all his publication are highly influential or has an equally high impact.

⁸ Documented by authors. Processed through Biblioshiny using R

Author	h_index	g_index	m_index	Total citations	Number of publications	Publication year
ZHANG Y	9	12	1.5	353	12	2020
LIU Y	7	7	1.2	260	7	2020
BEKUN FV	6	6	1.2	676	6	2021
VYSOCHAN O	6	10	1.2	102	10	2021
CHURCH KS	5	6	0.8	106	6	2020
DE VILLIERS C	5	6	1.3	221	6	2022
LI Y	5	6	0.8	79	6	2020
SCARPELLINI S	5	5	0.8	287	5	2020
SCHALTEGGER S	5	6	0.8	220	6	2020
SMITH SS	5	6	0.8	104	6	2020
WANG Z	5	5	1.3	69	5	2022

Table 5: Authors local impact by h-index⁹

Leading countries

One of the research questions in this study explores which are the most prominent countries leading the research output in these fields and which are the countries/regions where more should be done to incentivize the research. Table 6 and Figure 3 presents the number of publications for the top ten countries. What is noticeable is that the countries that produce the most articles are the USA and China, which are very developed countries and can be considered as leading countries in scientific research. In third place is ranked Italy, a country that is increasingly contributing to accounting literature on the various areas related to technological developments and sustainability reporting. Figure 3 represents visually the research output distribution. Dark blue colored countries, represent countries that have the highest number of publications within the timeframe studied, while countries colored in light blue have few publications, Gray areas represents countries that have very few contributions like Albania, Bulgaria etc. or countries that have not contributed to this research field, like Montenegro.

Region	Freq
USA	733
CHINA	590
ITALY	368
UK	273

⁹ Documented by authors. Processed through Biblioshiny using R

AUSTRALIA	258
UKRAINE	216
INDONESIA	179
INDIA	165
SPAIN	143
GERMANY	136

Table 6: Articles published per country¹⁰

Country Scientific Production

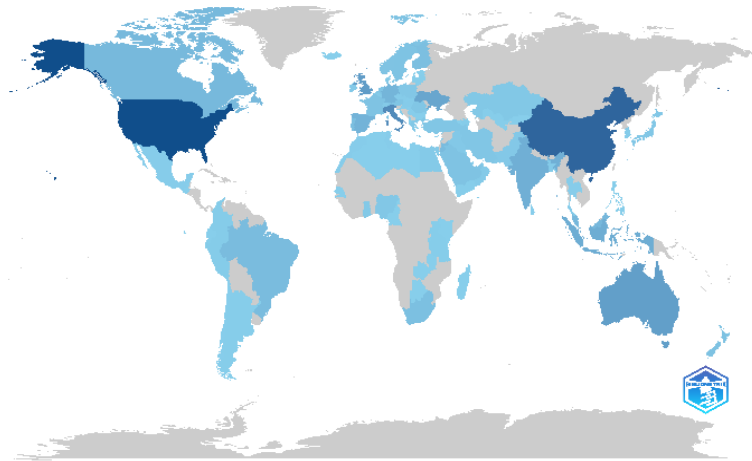


Figure 3: Articles published per country¹¹

Figure 4 illustrates the cumulative occurrences of different research terms in studies published between 2020 and 2024. The most frequently occurring word is “Sustainable development”, representing a growing usage of this terms. This trend is explained by the increased global focus on sustainability issues. This term is followed by “sustainability”, which has also a growing trend but at a lower rate than “Sustainable development”. Other terms such as life cycle, innovation, have a growing trend but not at such high rates. It is also notable that the term with the lowest cumulative occurrence across terms analysed, is artificial intelligence, a reason for this could be that AI is still being developed as a subfield of sustainability, and because it was only at the end of 2022 that open source AIs were made available to the public, and hence increase the research interest on the field.

¹⁰ Documented by authors. Processed through Biblioshiny using R

¹¹ Documented by authors. Processed through Biblioshiny using R

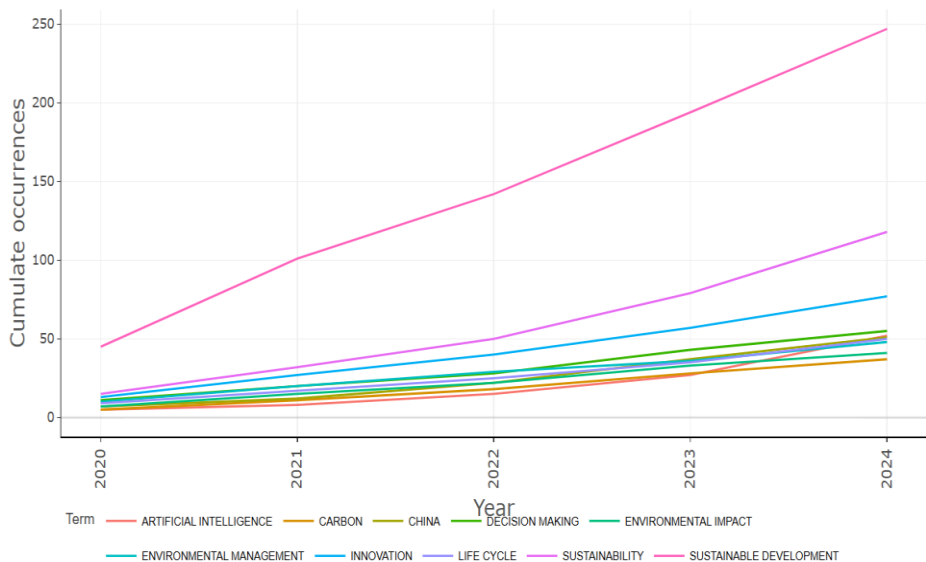


Figure 4: Cumulative occurrences¹²

Co-occurrence keyword analysis

Figure 5 illustrates a co-occurrence keyword analysis, which investigates the relationship between frequently used terms. The co-occurrence is defined in this study as the presence of two terms in the same document, representing their thematic relationship and relevance. The network graph analyses visually the relationship among topics related to sustainable development. The larger the size of the text, the more important and frequent the term is. The colors of clusters represent different topics, such as sustainability development, economic growth, blockchain, and artificial intelligence. The analysis highlights that AI, blockchain, and big data play a crucial role in enforcing sustainable practices. Whereas sustainable development is more closely related with cost accounting, and cost-benefit analysis.

¹² Documented by authors. Processed through Biblioshiny using R

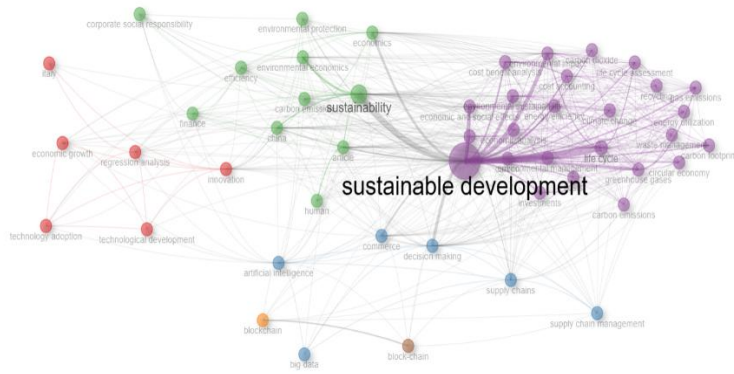


Figure 5: Keyword co-occurrence¹³

Figure 6 illustrates the evolution of the terms' trend for the study period, 2020 to 2024. The larger the size of the bubble, the more the term is used. *Cost analysis*, *life cycle assessment*, and *risk assessment* were the most commonly used terms during 2020 – 2021. By 2022, the focus shifts from these terms to *sustainable development*, *sustainability*, *artificial intelligence*, *China*, and *energy-related topics*. The prominence of "China" among publications studied, reinforces its critical role in leading global sustainability policies and technological developments and the increased interest in studying the phenomena and hence its increased presence in the published research. The increasing usage of terms related to carbon emissions and greenhouse gases further confirms the importance of environmental impact issues in financial and sustainability reporting.

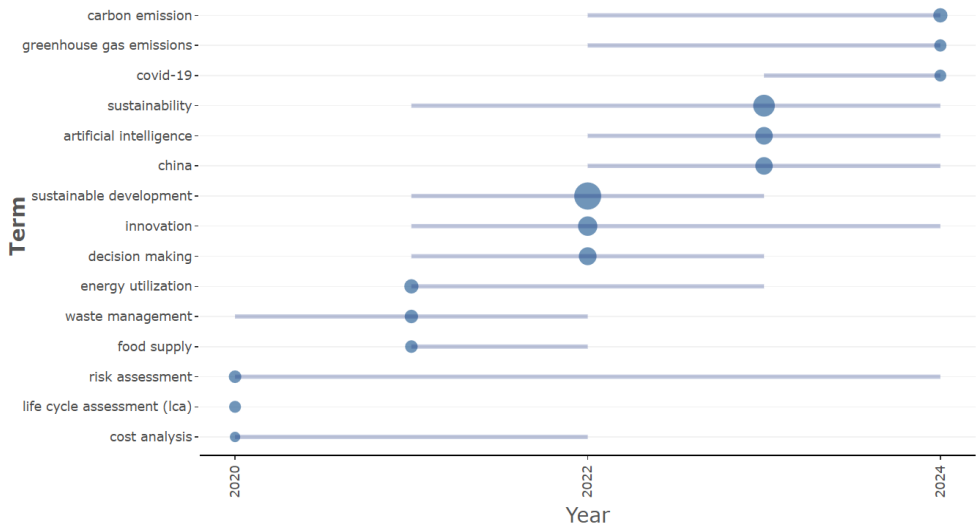


Figure 6: Trend topics from 2020 to 2024

¹³ Documented by authors. Processed through Biblioshiny using R

5. Main findings and Conclusions

Through a thorough bibliometric analysis of 1,603 publications retrieved from the Scopus database from 2020 – 2024 this study provides valuable insights into emerging trends of accounting research topics. The findings show an increased academic interest in the intersection of digitalization and sustainability in accounting, with an average annual growth rate of 25.4%.

RQ1: Which is the main focus of research when it comes to both digitalization of accounting and sustainability? Is there a connection/intersectionality dimension between digitalization and sustainability reporting?

Bibliometric mapping reveals a strong intersection between digitalisation of accounting and sustainability in accounting research. Despite this intersection, the keyword with the lower cumulative occurrence is artificial intelligence (AI), a reason for this could be that AI is still being developed as a subfield of sustainability, and because it was only by the end of 2022 that open source AIs were made available to the public, and hence increase the research interest on the field.

RQ2: Which are the highest-ranking journals in terms of publications in digitalization of accounting and sustainability and who are the most productive authors in these fields?

The highest ranking Journals in terms of publications in the field of digitalization and sustainability are: Journal of Cleaner Production and the Accounting, Auditing & Accountability Journal. These journals are valuable sources for researchers whose research areas are in the intersectionality of the digital accounting and sustainability and serve as primary sources of their search and literature review. Results reveal that authors who have the highest h-index are Zhang Y, Liu Y, and Bekun FV. Future researchers on the digitalization of accounting and sustainability can rely on these authors, who have published in high-impact journals and are the most cited.

RQ3: Are there any prominent countries that lead the research, and which are the countries/regions where more should be done to incentivize the research?

Prominent countries that lead the research are the United States and China, which are very developed countries and can be considered as leading countries in scientific research. A reason that China is one of the most productive countries can be explained by the fact that China is also a leader in global sustainability policies and technological developments. The research is followed by Italy, a country that is increasingly contributing to the literature on the various developments that accompany accounting.

RQ4: What is the trend of terms used in conducting a research paper focused on accounting and sustainability and what is the shift in this trend if any?

By analyzing the topics' trends during the period covered from 2020-2024, a shift in the use of the terms was noticed within this period. This study reveals that studies published during 2020 - 2021 were focused on topics such as cost analysis, life cycle assessment, and risk assessment. By 2022 accounting research became more oriented toward broader and up-to-date themes such as sustainable development, artificial intelligence, and energy-related topics, reflecting the ChatGPT introduction and the widespread use of this tool and other similar tools that followed. These trends emphasize a transformative research realm, in which digital tools, automation, and AI are an integral part of sustainable accounting practice.

6. Limitations and further research

We analyzed the Scopus Database of the recent 5 years (2020 – 2024), focusing on the trend of key terms digitalization of accounting, blockchain, sustainability and sustainable developments.

Our specific focus is on the recent five years of research and on the interrelation between the digitalization of the accounting field and sustainability reporting and how these terms have been researched specifically in the five recent years. We find the highest ranking Journals in terms of publications in digitalization and sustainability are: the Journal of Cleaner Production and the Accounting, Auditing & Accountability Journal. These journals may serve as valuable point of reference for researchers interested in the intersectionality of digital accounting and sustainability. Our research also contributes by identifying the highest h-index authors being Zhang Y, Liu Y, and Bekun FV. Again, this is beneficial for future researchers on the digitalization of accounting and sustainability, who can rely on these authors, to refer to their work and increase the impact of their research.

This study offers valuable insights, but it also carries several limitations. The documents analysed through bibliometrics rely only on the Scopus database. Future researchers can use other databases like Web of Science or Google Scholar to conduct similar analyses. The period covered in this study is limited to 5 years, not considering previous studies. Another limitation of this paper is the exclusion of all papers in other languages besides English. Furthermore, this paper only considers articles published in scientific journals, leaving aside books, conference papers, editorials, etc. The present study is a paper that uses the quantitative method to achieve its objectives; future researchers can employ a qualitative analysis to further complement this research.

Possible future research can focus on analyzing the factors that contribute towards the low number of publication and research coming from non – US based journals. As we evidence that countries leading the research are the United States and China globally, and Italy in

Europe, a further extension of the research could be focused on specific factors that cause this noticeable gap.

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SMART AND INNOVATIVE STRATEGIES IN MARKETING USING AI

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Oana PREDA²

Abstract

In an era dominated by big data and digital interactions, adopting AI in marketing is no longer just a competitive advantage, but a necessity. In the transformative era of generative artificial intelligence (GenAI) in marketing, the vast potential of AI to revolutionize marketing strategies through advanced personalization and efficiency is becoming apparent, leading to a rapid rate of adoption among companies and marketing professionals. As companies seek to improve lead generation, qualification, and conversion, AI-powered tools are becoming essential. Consumers expect personalized messages, rapid interactions, and relevant offers, and AI enables brands to respond to these demands in an efficient and scalable way, with benefits including improved personalization, campaign automation, content optimization, predictive analytics, and more.

Keywords: artificial intelligence; marketing; AI integration in marketing; marketing strategy using AI.

JEL Classification: D83; L81; L86; M15; M31; O32; O33

1. Introduction – AI and its impact on marketing

Artificial Intelligence is no longer a concept from the future, but a tangible reality that is increasingly present in our lives. Although only 35% of companies worldwide currently use AI, according to a McKinsey & Company study, their number is set to almost double in the near future.[1]. According to McKinsey & Company, artificial intelligence applications have the potential to contribute \$2.6–4.4 trillion annually to the global economy [2] through various business scenarios.

In fact, the generative artificial intelligence (generative AI) market has evolved rapidly in 2024, moving from initial cultural fascination to tangible results in the business environment. This technology, with its ability to process and generate text, voice, and video content, is revolutionizing the way companies improve productivity and stimulate innovation and creativity. In fact, in this decade's economy, driven by the widespread

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introduction of AI, there will be a rapid transition to other skills: from simply performing repetitive and analytical tasks to creativity, critical thinking, empathy, and the ability to build human connections. If they do not adapt to the new requirements, almost 50% of current jobs will disappear in the near future. [2]

In this context, artificial intelligence is being integrated into more and more areas of activity, particularly in IT, marketing, medicine, e-commerce, and the automotive industry, but the impact of AI will be increasingly significant in all types of business. Thus, 72% of executives believe that artificial intelligence will become the most important business advantage in the future, according to data from McKinsey & Company.[3]

The current period promises to be an intense one for the business environment, with major trends that will change the way companies operate. One of the most important trends is the adoption of generative artificial intelligence. These technologies enable the creation of personalized content, process optimization, and the automation of repetitive tasks. For example, e-commerce companies can use generative AI to create compelling and relevant product descriptions. According to a McKinsey report, these technologies not only reduce operating costs, but also enable service personalization and improved customer relationships. [4]



Source: <https://www.qrcode-tiger.com/ro/>

Thus, as data volumes grow, AI technology helps organizations simplify complex processes and improve decision-making by analyzing historical data, identifying patterns, and forecasting future outcomes. Artificial intelligence is driving a major transformation in business operations, making tasks more efficient and data-driven.

In the field of marketing, as the future of artificial intelligence develops, this technology is transforming the way businesses interact with customers and understand market dynamics. Intelligent data analysis provides companies with a comprehensive view of customer behavior, market trends, competitor strategies, and operational performance.

At the same time, marketing automation uses software to simplify marketing processes such as customer segmentation, data integration, and campaign management, improving

decision-making and increasing ROI (Return on Investment). In this context, artificial intelligence (AI) plays an essential role, analyzing large volumes of data to predict customer behavior, enabling the creation of personalized campaigns and the automation of repetitive tasks.

Effective marketing automation includes key components such as data collection, segmentation, triggers, and personalized goals. [5]

This also brings up the prospect of economic efficiency, with savings evident in tasks that traditionally involve high external costs, such as content creation and market research. AI's ability to simplify these processes can reduce dependence on external resources, thereby lowering overall costs. AI-based personalization and technical tasks such as programming also benefit from cost reductions. [6]



Source: <https://www.qrcode-tiger.com/ro/>

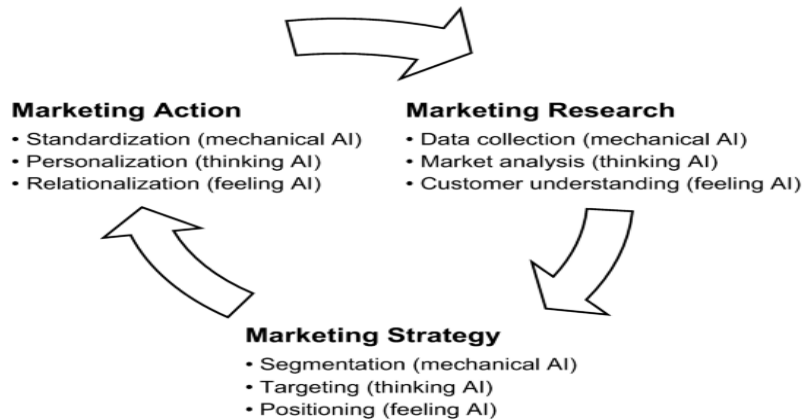
With regard to strategic marketing planning, which incorporates several benefits of AI, a three-stage framework for strategic marketing planning has been developed , [7], namely:

- ☐ Mechanical AI for automating repetitive marketing functions and activities;
- ☐ Thinking AI for data processing and decision making;
- ☐ Feeling AI for analyzing human interactions and emotions.

This framework presents ways in which AI can be used for marketing research, strategy (segmentation, targeting, and positioning—STP), and actions.

- In the marketing research stage, mechanical AI can be used for data collection, thinking AI for market analysis, and feeling AI for understanding customers.
- In the marketing strategy (STP) stage, mechanical AI can be used for segmentation (segment recognition), thinking AI for targeting (segment recommendation), and feeling AI for positioning (segment resonance).
- In the marketing action stage, mechanical AI can be used for standardization, thinking AI for personalization, and feeling AI for relationship building. We apply

this framework in different areas of marketing, organized according to the 4Ps/4Cs of marketing, to illustrate the strategic use of AI.



Source: Huang, Ming-Hui and Rust, Roland T., (2021), *A strategic framework for artificial intelligence in marketing*, Journal of the Academy of Marketing Science, 49, issue 1

Thus, AI technology is leading to a major transformation in business operations, making tasks more efficient;.[4] [Intelligent data analysis allows companies to understand past events, anticipate future trends, and make more informed decisions about potential actions.

2. Trends shaping the future of marketing in the context of technological progress

Staying up to date with ever-changing market trends is crucial to remaining competitive. [4] As marketing trends evolve alongside technological advances, businesses must adapt to remain relevant and effective in their promotional efforts.

- *Voice marketing* will have a stronger impact – voice marketing is one of three possible formats for interaction between customers and companies. Until a few years ago, textual interaction was mainly limited to postal correspondence and emails. Today, with the advent of chatbots and digital assistants, there is a new format for digital interaction. [8].

Voice marketing is an AI-powered solution that optimizes content with voice-activated systems so that products and services appear in voice search results. Leveraging voice assistant technologies such as Google Assistant, Alexa, and Siri empowers brands to revise their approaches for better customer satisfaction.

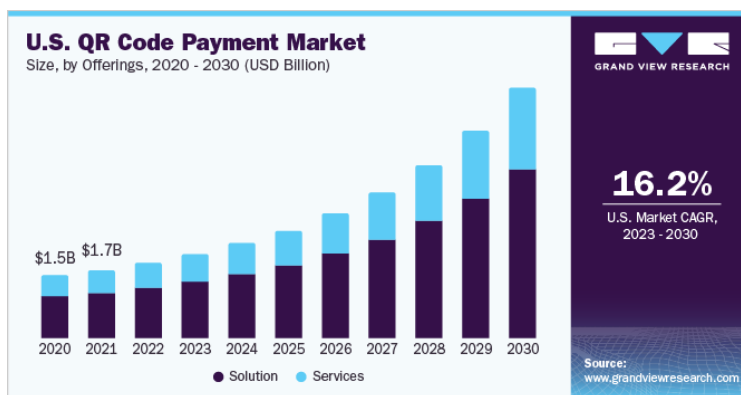
This spoken-word-based SEO technology creates new marketing avenues, paving the way for personalized interactions with users. Voice assistants can provide information about

products and services without necessarily requiring physical stores. This reduces the effort customers have to put into reading volumes of content or finding answers to their questions.

- *Visibility of QR codes on digital and printed materials*—QR code marketing is a trend to capitalize on in future marketing efforts. Major brands such as Coca-Cola, Nestle, IKEA, Starbucks, McDonald's, and others have demonstrated the advantages of these tools. Its innovation extends beyond product labels and is achievable through dynamic QR codes.

These editable and easily trackable elements are developed as future-oriented marketing tools, covering advanced features and multiple software integrations. This makes it an ideal tool for business, as codes are one of the most effective marketing techniques.

With its ability to incorporate information of up to 7089 numeric characters, 4296 alphanumeric characters, and 1817 Kanji characters, consumers can be provided with complete details, leaving no room for confusion. According to Grand View Research [10], the QR code market is projected to grow at an annual rate of 16.9% over the decade, reaching \$33.13 billion by 2030



Source: <https://www.grandviewresearch.com/>

This reflects the growing adoption of QR codes across various industries as a key component in creating engaging campaigns, creating animated advertisements, quickly distributing business information, and streamlining transactions. As businesses capitalize on the growing acceptance of QR codes, they are using this technology to design innovative campaigns, simplify transactions, and create meaningful digital touchpoints with their audience. The QR code revolution is redefining marketing, making it faster, smarter, and more engaging than ever before.

- *The emergence of conversational marketing strategies for stronger customer connections*—Conversational marketing has evolved significantly through the use of chatbots, live chats, and social media messaging apps, allowing brands to offer fluid and

personalized interactions beyond one-way advertising. This shift allows businesses to connect with potential customers across multiple channels, creating dynamic dialogues instead of relying on traditional monologues. Chatbots have played an important role in facilitating access to conversational marketing by simulating natural, informal conversations that engage users. Social messaging apps, such as WhatsApp, have become the preferred platform for these interactions.

With nearly 3 billion users, WhatsApp has proven to be an invaluable tool for businesses, helping them respond quickly and efficiently to customers. [4] In fact, WhatsApp was the third most downloaded app on Google Play in March 2024, with 33 million downloads. Through social messaging apps, companies can now answer product questions, gather feedback, and interact with customers conveniently and efficiently. This approach will become even more widespread in the coming years as companies seek to build stronger, more personal connections with their audiences.

A business's knowledge potential can be enhanced through technology, and these technological advances also contribute to improving customer interaction. Intelligent technologies, such as artificial intelligence, are transforming companies by collecting and analyzing vast amounts of data, which further improves customer interaction and experience. [9]

The greatest growth opportunity for companies today is the transition of customers from offline to online; as advanced technology users, they spend most of their time online and therefore expect a superior digital experience. Technological advances have simplified complex processes, allowing companies to create influential customer experiences with a single click.

To make real-time decisions, such as predictions and other marketing actions, machines present, learn, and store information based on previous and current knowledge and experience. Machines learn as they evaluate decisions, allowing them to respond and adapt to the dynamic business environment—something that was previously impossible to achieve using traditional methods.

- *Optimizing social networks for more personalized and targeted content* - Social media optimization (SMO) is a key strategy for companies that want to improve their online presence and engagement. By refining content, using trending hashtags, leveraging data analytics, and improving search engine visibility, companies can strengthen their impact on social platforms.



Source: <https://www.qrcode-tiger.com/ro/>

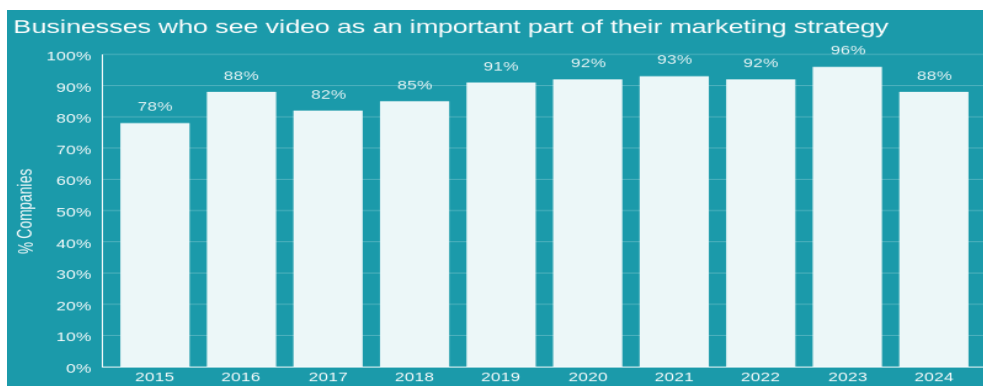
In the current context, popular social platforms such as TikTok, YouTube, Facebook, and Instagram will remain essential tools for shaping consumer behavior. These platforms have already revolutionized the way companies interact with their audience, and with advanced internet-based tools, companies can fine-tune their marketing strategies to achieve even more accurate results.

The Kepios Report Embed Issues — DataReportal – Global Digital Insights [12] analysis from October 2024 shows that social media usage continues to grow. There are approximately 5.22 billion social media users worldwide, representing 63.8% of the world's population. These figures reflect the scale that businesses need to take into account and the growing importance of SMOs in effectively reaching target audiences.

In fact, 94.5% of global internet users now interact with social media every month, highlighting the critical role these platforms play in modern marketing. With SMO, businesses can easily create personalized, targeted content that speaks directly to individual consumers.

- *Augmented video content will attempt to influence consumer behavior* – relevant is a survey [13] conducted by Wyzowl – one of the world leaders in the production of animated explanatory videos – in which 967 unique respondents participated. One of the conclusions was that the use of videos as a marketing tool has grown steadily over the past 8 years. In 2016, only 61% of brands used videos – a percentage that reached a record high of 91% in 2023 and 2024.

Although the percentage of businesses using video has remained the same since 2023, the number of marketers who consider video content essential has declined slightly. In 2024, 88% of companies consider video a crucial part of their marketing strategy, down from 96% in 2023.



Source: Wyzowl State Of Video Marketing Report 2024: Key Insights And Takeaways

Video marketing appears promising, with 90% of marketers acknowledging that they have achieved a good ROI from it. Although this percentage has decreased slightly from 92% in 2023, the change is not significant.

- ✓ 60% of marketers measure ROI based on video engagement, analyzing likes, comments, shares, and reposts.
- ✓ 42% of brands use audience engagement and customer retention as metrics
- ✓ 40% of specialists calculate ROI based on the number of video views.
- ✓ 39% of brands measure ROI using brand awareness or PR.
- ✓ Surprisingly, only 32% of brands use net sales, i.e., the net revenue generated during the period when the video was published, as a method of calculating ROI
- ✓ 28% use the number of clicks on the video or leads as a measure of quantification.

With a 90% share, YouTube is the most widely used video marketing channel by companies. Facebook ranked second, followed by Instagram. Virtual reality, Snapchat, and 360° videos were at the bottom of the list. When it comes to the effectiveness of these video marketing channels, YouTube, Facebook, and Instagram again took the top three spots.

The report clearly shows that video marketing remains relevant. There is strong evidence to suggest that the coming years will be dominated by video content. Videos are highly visual, engaging, entertaining, and interactive, allowing users to obtain a lot of information in a short amount of time. This is why most customers prefer to interact with brands through videos. It is clear that videos have a powerful impact and the potential to generate leads, increase traffic, and improve conversions.

3. Conclusions

The adoption of artificial intelligence in marketing is no longer just a competitive advantage, but an essential condition for the survival and development of companies in a dynamic digital environment. Data analysis, process automation, and interaction personalization enable organizations to respond quickly and efficiently to consumer demands, while increasing performance and return on investment.

Current trends - such as conversational marketing, QR code integration, social media optimization, and increased video content relevance - underscore the central role of AI technologies in redefining the relationship between brands and customers. Furthermore, the strategic framework based on mechanical, thinking, and feeling AI demonstrates that artificial intelligence can be used not only for efficiency, but also for enhancing creativity and emotional connections with consumers.

Therefore, the future of marketing will be dominated by intelligent, scalable, and innovative solutions capable of transforming data into actionable insights and creating personalized experiences with a real impact on consumer behavior. Organizations that know how to strategically integrate these technologies will not only gain a competitive advantage but also increased resilience in the face of rapid market changes.

Artificial intelligence (AI) is driving a major transformation in business operations, making tasks more efficient and data-driven. As the future of AI in marketing unfolds, this technology is transforming how businesses interact with customers and understand market dynamics.

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ENHANCING LAYER 2 SECURITY IN NETWORK SWITCHES

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Dragoș POP³

Abstract

Layer 2 (L2) security is a critical aspect of network infrastructure, as threats such as MAC flooding, STP manipulation, and ARP spoofing can compromise data integrity and network availability. Modern switches offer several security mechanisms—such as port security, BPDU guard, root guard, and dynamic ARP inspection (DAI)—to mitigate these risks. This article provides an in-depth analysis of these security features, explaining their operational principles, implementation strategies, and best practices. Additionally, CLI configuration examples are included to demonstrate real-world applications in securing enterprise networks.

Keywords: Layer 2 security, port security, BPDU guard, root guard, dynamic ARP inspection, MAC flooding, STP manipulation, ARP spoofing

JEL Classification: C69; C88; L63; L86.

1. Introduction

Layer 2 security is fundamental to the stability and security of an enterprise network. Because Layer 2 operates without inherent authentication mechanisms, attackers can exploit weaknesses to launch various attacks, such as:

- MAC flooding attacks, where an attacker overwhelms a switch's MAC address table, forcing it to flood unicast traffic to all ports.

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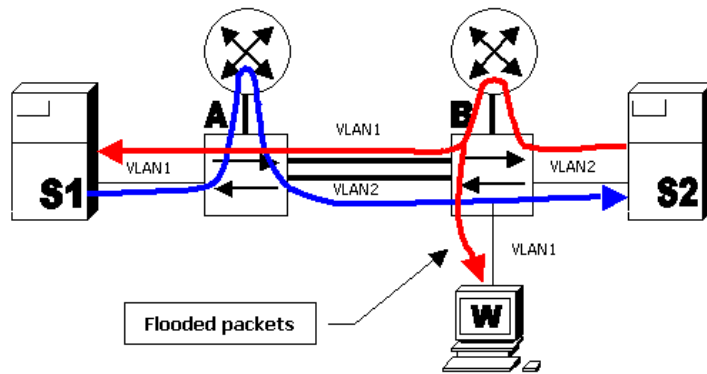


Figure 1. Unicast Flooding in Switched Campus Networks ⁴

- Spanning Tree Protocol (STP) manipulation, where an attacker injects malicious BPDUs to alter network topology.

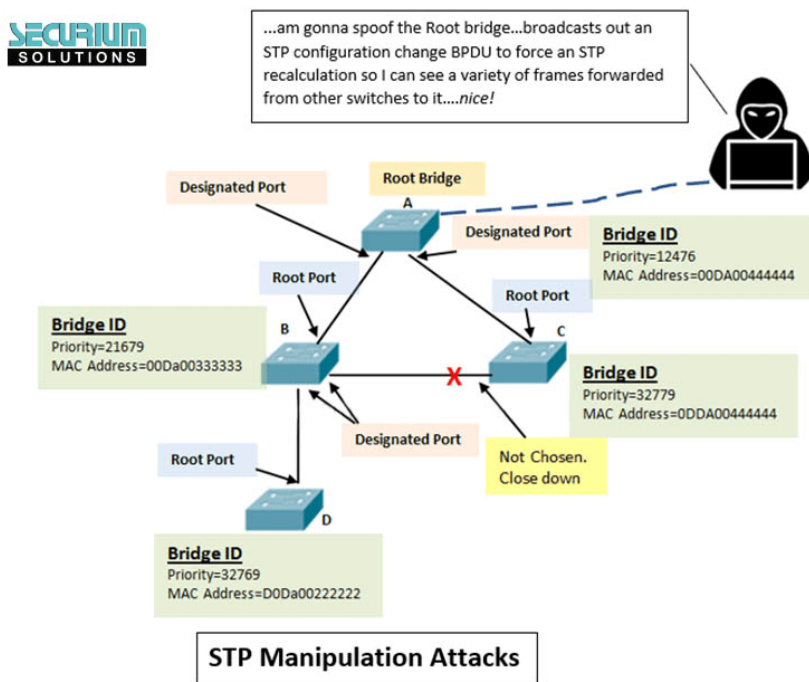


Figure 2. STP manipulation attacks ⁵

⁴ Source: <https://cisco.com>

⁵ Source: <https://securiumsolutions.com>

- ARP spoofing attacks, which allow an attacker to redirect or intercept network traffic.

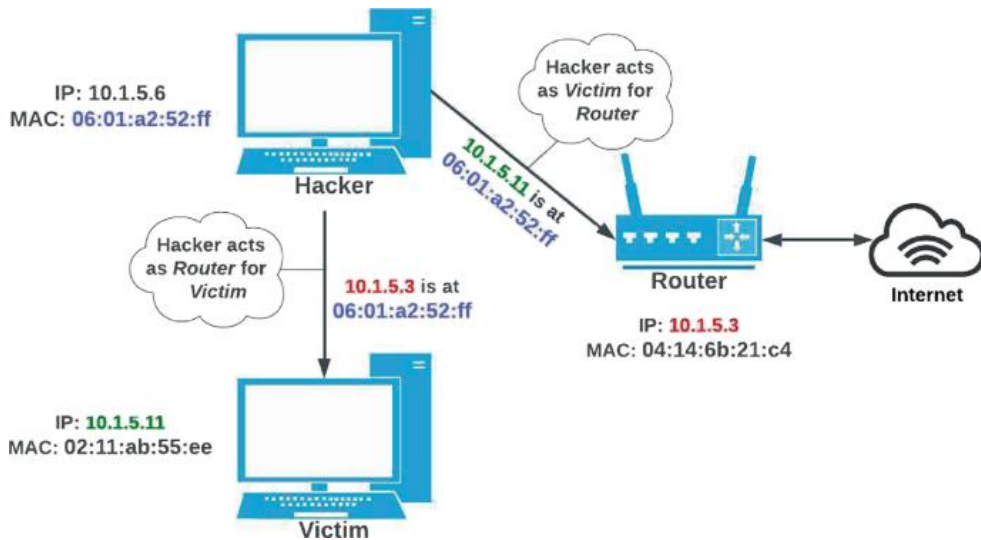


Figure 3. ARP spoofing ⁶

To counter these threats, network engineers can implement switch-level security mechanisms that enforce traffic control and integrity checks. This paper discusses four key L2 security features: port security, BPDU guard, root guard, and dynamic ARP inspection (DAI), along with CLI configuration examples.

2. Layer 2 Security Features and Configuration

2.1 Port Security

Port security restricts the number of MAC addresses allowed on a switch port, preventing unauthorized devices from accessing the network. This feature is particularly effective against MAC flooding attacks.

⁶ Source: https://link.springer.com/chapter/10.1007/978-981-99-3010-4_33

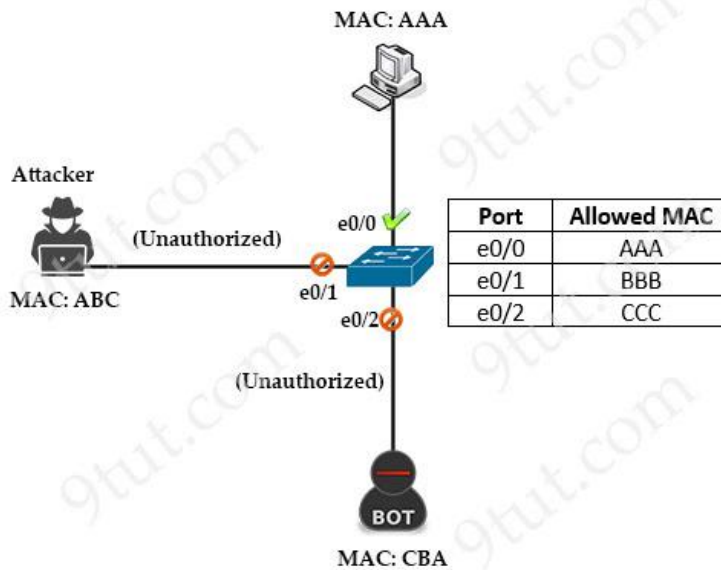


Figure 4. CCNA Training - Port Security⁷

To configure port security on a Cisco switch:

```
Switch(config)# interface FastEthernet 0/1
Switch(config-if)# switchport mode access
Switch(config-if)# switchport port-security
Switch(config-if)# switchport port-security maximum 1
Switch(config-if)# switchport port-security mac-address
00A1.B2C3.D4E5
Switch(config-if)# switchport port-security violation restrict
```

2.2 BPDU Guard

BPDU Guard prevents unauthorized BPDU packets from being sent into the network, mitigating the risk of malicious STP manipulation.

⁷ Source: <https://www.9tut.com/port-security-tutorial>

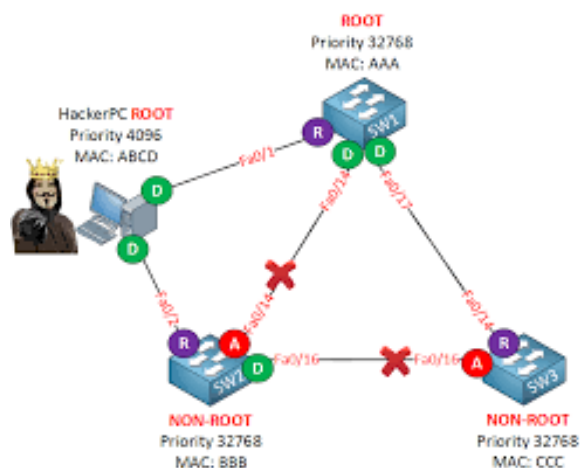


Figure 5. Spanning Tree BPDU Guard⁸

To enable BPDU Guard on an access port:

```
Switch(config)# interface FastEthernet 0/1
Switch(config-if)# spanning-tree portfast
Switch(config-if)# spanning-tree bpduguard enable
```

2.3 Root Guard

Root Guard ensures that unauthorized switches cannot become the STP root bridge, preventing potential STP topology manipulation.

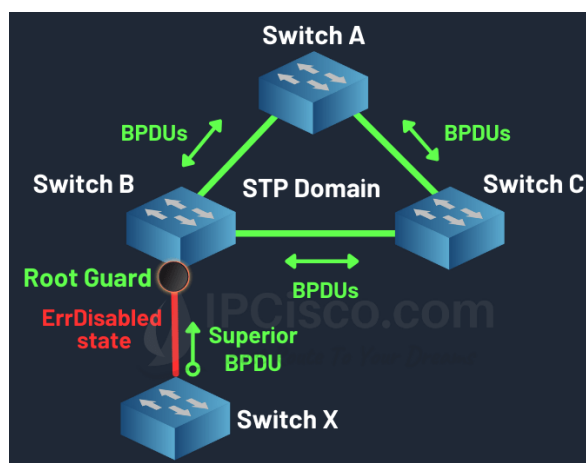


Figure 6. Spanning Tree BPDU Guard⁹

⁸Source: <https://networklessons.com/cisco/ccie-enterprise-infrastructure/spanning-tree-bpduguard>

⁹Source: <https://ipccisco.com/lesson/stp-root-guard/>

To enable Root Guard on an interface:

```
Switch(config)# interface FastEthernet 0/2
Switch(config-if)# spanning-tree guard root
```

2.4 Dynamic ARP Inspection (DAI)

Dynamic ARP Inspection (DAI) helps prevent ARP spoofing by verifying ARP packets against a trusted database.

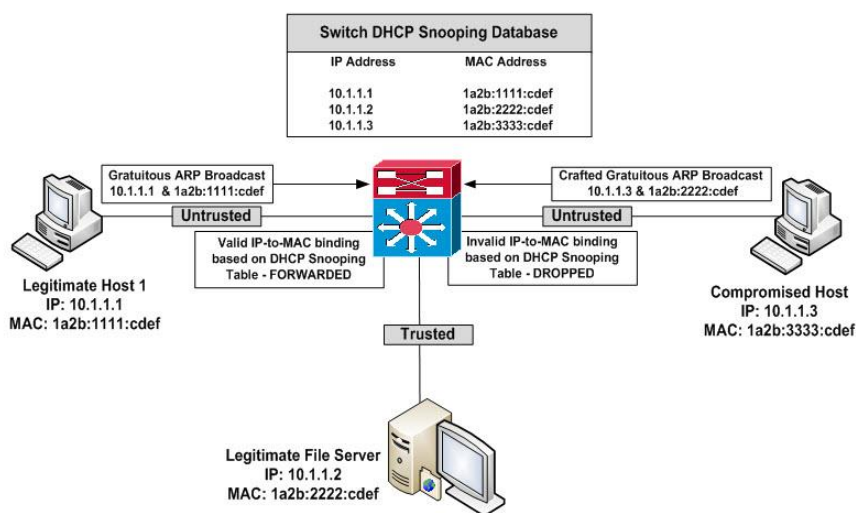


Figure 7. Spanning Tree BPDU Guard¹⁰

To enable DAI on VLAN 10:

```
Switch(config)# ip dhcp snooping
Switch(config)# ip dhcp snooping vlan 10
Switch(config)# ip arp inspection vlan 10
```

3. Additional Examples of Layer 2 Attacks and Mitigations

Building on the core features discussed, here are expanded real-world examples of Layer 2 threats and how the recommended security mechanisms (port security, BPDU guard, root guard, and DAI) can mitigate them. These scenarios illustrate practical applications in enterprise environments.

¹⁰ Source: <https://www.howtonetwork.com/certifications/cisco-2/dynamic-arp-inspection-explained/>

3.1. MAC Flooding in a Corporate Office

Scenario (Unprotected Network): In a mid-sized office with 200 employees connected via unmanaged switches, an insider connects a rogue device running a MAC flooding tool (e.g., macof from the dsniff suite). This floods the switch's CAM table with thousands of fake MAC addresses, causing the switch to enter "fail-open" mode and broadcast all traffic like a hub. Sensitive data from VoIP calls and file shares becomes sniffable across the LAN, leading to data exfiltration.

Mitigation with Port Security: Configure port security to limit each access port to 2-3 learned MAC addresses (e.g., for a laptop and IP phone). Upon violation, the port enters "restrict" mode, logging alerts without shutdown. This prevents table exhaustion while allowing legitimate multi-device use.

CLI Example Extension:

```
Switch(config)# interface range FastEthernet 0/1 - 24
Switch(config-if-range)# switchport port-security maximum 2
Switch(config-if-range)# switchport port-security violation restrict
Switch(config-if-range)# switchport port-security aging time 2
```

3.2. STP Manipulation in a Data Center

Scenario (Unprotected Network): A contractor plugs in a rogue switch configured to send superior BPDUs, claiming a lower bridge ID. This manipulates the STP root election, redirecting all traffic through the attacker's device. In a data center with high-traffic servers, this causes latency spikes, packet loss, and potential loops, halting operations for hours.

Mitigation with BPDU Guard and Root Guard: Enable BPDU Guard on edge ports to immediately disable them upon rogue BPDU detection. Use Root Guard on inter-switch links to block superior BPDUs without full shutdown, preserving partial topology.

CLI Example Extension:

```
Switch(config)# spanning-tree portfast bpduguard default
Switch(config)# interface GigabitEthernet 1/0/1
Switch(config-if)# spanning-tree guard root
```

3.3. ARP Spoofing in a Hybrid Work Environment

Scenario (Unprotected Network): A remote worker's compromised VPN endpoint allows an attacker to ARP poison the local subnet upon reconnection. The attacker impersonates the gateway, intercepting credentials and session cookies from cloud apps, leading to lateral movement into CRM systems.

Mitigation with DAI: Integrate DAI with DHCP snooping to validate ARP replies against a binding table. Untrusted ports drop invalid packets, ensuring only legitimate IP-MAC mappings propagate.

CLI Example Extension:

```
Switch(config)# ip dhcp snooping database flash:/dhcp-snooping.db
Switch(config)# interface GigabitEthernet 1/0/2
Switch(config-if)# ip dhcp snooping trust
```

4. Comparison: Protected vs. Unprotected Layer 2 Networks

The table below compares outcomes in unprotected versus protected networks across key metrics, based on common attack vectors. Protected networks implement the features from Section 2.

Aspect	Unprotected Network	Protected Network (with Port Security, BPDU/Root Guard, DAI)
Attack Success Rate	High: 80-90% of L2 attacks succeed without mitigations (e.g., ARP spoofing intercepts 100% of traffic).	Low: <10% success; features drop invalid packets/BPDUs, limiting exposure to verified devices.
Detection Time	Delayed: Attacks often go unnoticed for days/weeks, as traffic anomalies mimic congestion.	Immediate: Logging and port shutdowns trigger alerts within seconds (e.g., syslog for violations).
Downtime Impact	Severe: MAC flooding causes 100% broadcast mode, leading to 30-60 min outages per incident.	Minimal: Restrict mode logs without full shutdown; recovery <5 min via manual clear.
Data Exposure Risk	Total: Eavesdropping on all LAN traffic, enabling credential theft in 70% of cases.	Isolated: Only trusted MACs/IPs allowed; MITM blocked, reducing exposure by 95%.
Recovery Cost	High: \$50K-\$200K per incident (forensics, lost productivity); e.g., STP loops require full topology rebuild.	Low: \$1K-\$5K; automated bindings and guards enable quick rollback without external audits.

Aspect	Unprotected Network	Protected Network (with Port Security, BPDU/Root Guard, DAI)
Example Scenario	Rogue DHCP server assigns malicious IPs to 50% of devices, diverting traffic for weeks.	DAI drops rogue replies; DHCP snooping limits to trusted servers, preventing diversion.

This comparison highlights how protections enforce trust boundaries, transforming reactive firefighting into proactive defense.

5. Statistics on Layer 2 Attacks

While Layer 2 attacks are underreported compared to higher-layer threats (due to their internal nature), recent data underscores their prevalence:

- **Frequency:** In 2024, 46% of organizations reported increased DDoS-like floods, many rooted in L2 exploits like MAC flooding; application-layer attacks (often enabled by ARP spoofing) rose 15% YoY. Globally, cyber attacks surged 30% in Q2 2024, with L2 manipulation (e.g., STP) contributing to 20-25% of LAN disruptions in enterprises.
- **Impact:** ARP spoofing accounts for ~40% of MITM incidents in unsecured LANs, leading to \$4.45M average breach cost (up 15% from 2023). In PSK networks, a single compromised key enables L2 attacks in 90% of cases, expanding to full network compromise.
- **Trends (2025):** Q2 2025 saw 7.3M DDoS mitigations, with L2 precursors (e.g., CAM overflows) in 21% YoY growth for tech sectors. 94% of SMBs faced at least one attack in 2024, many L2-based due to flat networks.

These figures emphasize L2 as a "silent" vulnerability, often escalating to multimillion-dollar breaches.

6. Performance Impact of Security Features

Modern switches (e.g., Cisco Catalyst) handle these features with minimal overhead, but tuning is essential to avoid bottlenecks:

- **Port Security:** Negligible impact (<1% CPU/memory); limits MAC learning per port without deep inspection. On high-traffic ports, "sticky" learning adds ~0.5ms latency during initial binds. Rare issues: Excessive violations can fill logs, requiring rotation.

- **BPDU Guard/Root Guard:** Zero runtime overhead; passive monitoring only activates on anomaly (e.g., BPDU receipt), blocking in <1ms. No measurable throughput loss; ideal for edge ports.
- **Dynamic ARP Inspection (DAI):** Moderate ingress overhead (2-5% CPU on Catalyst 9000 series for 1Gbps traffic); validates ARP packets against bindings, adding 10-50µs per packet. High-volume environments (e.g., 10Gbps) may see 5-10% drop if untrusted ports flood—mitigate with rate-limiting (e.g., 15pps). Err-disable on rate exceed (e.g., >100 ARPs/sec) prevents DoS but requires monitoring.

Feature	CPU Overhead	Latency Added	Best Practice for Performance
Port Security	<1%	<1ms	Use "restrict" over "shutdown"; age static MACs.
BPDU/Root Guard	0%	<1ms (on block)	(on Enable globally on PortFast ports.
DAI	2-5%	10-50µs	Trust uplink ports; integrate with DHCP snooping.

Overall, impacts are sub-5% on gigabit+ hardware, far outweighed by attack prevention. Test in lab for custom topologies.

7. Conclusions

The security of Layer 2 networks is paramount to ensuring overall network stability. Port security, BPDU guard, root guard, and dynamic ARP inspection provide essential safeguards against common Layer 2 attacks. By implementing these features with best practices, network administrators can significantly reduce the risk of unauthorized access, topology manipulation, and ARP spoofing.

Incorporating these examples, comparisons, statistics, and performance insights reinforces that Layer 2 protections are low-cost, high-reward. Enterprises ignoring them risk 80%+ higher breach likelihood, while adoption yields resilient, performant networks.

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CONVERGENCE OF EDUCATION, TECHNOLOGY AND AUTHENTICITY: THE CHALLENGE OF DESIGNING A UNIVERSITY E-LEARNING PLATFORM

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Abstract

The rapid evolution of digital technologies has redefined the landscape of higher education, pushing institutions worldwide to reconsider traditional models of knowledge delivery. This article explores the conception, development, and implementation of RAU Academy Education, a university-level asynchronous video-learning platform launched by the Romanian-American University. The platform emerged as a response to the increasing demand for flexibility, digital accessibility, and personalized learning experiences. Through the lens of authenticity and institutional responsibility, the article analyzes the opportunities, benefits, and challenges that accompanied this initiative — both from the perspective of students and academic staff. Lessons learned throughout this transformative journey offer valuable insights for institutions seeking to develop sustainable, mission-driven educational platforms in the post-digital age.

Keywords: e-learning, digital education, higher education innovation, asynchronous learning, Romanian-American University

JEL Classification: I23, O33, D83

1. Introduction – The Educational Crossroads

The global landscape of higher education is undergoing a profound transformation. In the aftermath of the COVID-19 pandemic and amid the accelerating pace of technological advancement, universities are facing growing pressure to reimagine their educational delivery models [3]. Students no longer perceive learning as confined to lecture halls or synchronous interactions. Instead, they seek flexibility, autonomy, and access to knowledge that transcends spatial and temporal boundaries. These shifts reflect a deeper societal transition: one that positions digital literacy and personalized learning at the center of academic relevance and institutional sustainability [1].

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Asynchronous learning platforms have emerged as a key component of this transformation. They allow learners to access curated, on-demand content at their own pace, breaking the barriers imposed by fixed schedules and geographic constraints. More than a technical solution, such platforms reflect a change in educational culture—one that emphasizes student agency, adaptive pedagogy, and a growing commitment to inclusion.

However, the implementation of asynchronous systems within traditional universities remains uneven and often fragmented. While many institutions have adopted hybrid or fully online teaching methods, few have succeeded in developing sustainable platforms that also retain a sense of academic authenticity. The tension between digital innovation and the preservation of institutional identity is real—and it demands a nuanced approach to platform design.

This article presents the case of *RAU Academy Education*, the asynchronous video-learning platform developed by the Romanian-American University, as a response to this educational crossroads. The article offers a reflective analysis on the process of envisioning, designing, and launching the platform, exploring both the opportunities it unlocked and the challenges it posed—for students, professors, and the university as a whole.

2. Institutional Context and Strategic Vision

Founded as a private institution with a mission to blend academic excellence and practical relevance, the **Romanian-American University (RAU)** has long championed innovation in education. Positioned at the intersection of business, technology, and social sciences, the university has consistently embraced digital transformation as a core strategic pillar. The Faculty of Computer Science for Business Management, in particular, has played a leading role in fostering this vision.

The conception of *RAU Academy Education* was born out of a broader institutional effort to create long-term value for learners and educators alike. Rather than acting in response to crisis (as was the case for many institutions during the pandemic), the platform was designed as a **strategic initiative**, aimed at complementing traditional education with high-quality digital learning experiences[2]. This decision reflected not only an awareness of global educational trends, but also a commitment to remaining relevant in a rapidly evolving academic ecosystem.

Central to the platform's strategic vision were the following goals:

- **Empowerment of students** through flexible, self-paced access to academic content;
- **Increased visibility and digital footprint** for RAU and its faculty;

- **Encouragement of pedagogical innovation** through multimedia and modular teaching formats;
- **Establishment of a new academic product line**, blending certification, scalability, and accessibility;
- **Bilingual accessibility**, enabling content to be offered in both Romanian and English for wider reach.

Unlike many short-lived digital projects, RAU Academy Education was conceived as a **long-term institutional asset**—one that evolves through continuous contribution and adaptation. Its design principles were shaped by the belief that technology should not replace the teacher, but **amplify their reach and voice**, and that recorded lectures, when thoughtfully curated, can preserve the human dimension of teaching.

The platform was not developed in isolation. It was integrated into the university's strategic communications, governance structures, and academic planning processes. Professors were invited—not mandated—to contribute, and incentives were aligned to recognize their creative and educational labor. This intentional design laid the foundation for a platform that is not only technologically robust, but also **institutionally coherent and pedagogically meaningful**.

3. Platform Architecture and Design Philosophy

The design of *RAU Academy Education* was guided by a dual imperative: **pedagogical authenticity** and **technological simplicity**. In an age of sophisticated learning management systems and AI-enhanced delivery tools, the development team at the Romanian-American University deliberately chose a streamlined, modular architecture—one that would **lower barriers to contribution** for faculty members, and simultaneously **ensure clarity and usability** for students.

3.1. Technical Simplicity, Scalable Design

At its core, the platform leverages a web-based infrastructure that supports:

- **Video streaming**, optimized for desktop and mobile access;
- **Multilingual interface** (Romanian and English);
- **Secure digital payments** for course access;
- **User account management** with student progress tracking;

- **Content structuring** in clearly defined modules and chapters.

Rather than relying on heavyweight LMS solutions, *RAU Academy Education* adopted a **custom-tailored solution** that foregrounds the **course itself** rather than the surrounding system complexity [1]. The goal was to allow professors to focus on the quality of their content—**not on learning a new platform**.

Courses can be recorded live, during regular teaching sessions (especially during hybrid or online weeks), or in a more curated, pre-recorded format. Professors are given full flexibility, while the platform team provides **technical assistance** with editing, formatting, and publishing.

3.2. Content Ownership and Contribution Model

A unique aspect of RAU Academy's approach is its **non-exclusive licensing model**. Professors retain the rights to their content, and are rewarded with a **revenue share** from course sales. This aligns the platform with global trends in educational creator economies, empowering faculty to see themselves not only as instructors, but also as **authors and digital educators** with their own intellectual footprint [5].

This model also encourages **creative diversity**: while the university provides guidelines on course structure and duration (a minimum of 2.5 hours per course), the pedagogical style, language, and materials are left to the professor's discretion. This openness respects **individual academic voice**, and avoids the trap of rigid standardization.

3.3. Human-Centered Design

Beyond technical and economic considerations, the platform was shaped by a core belief: that **asynchronous learning must remain human**. While RAU Academy employs all the benefits of video editing and online delivery, it **preserves the presence of the professor** as a guide, not a narrator [4]. Recorded courses are not impersonal tutorials—they are expressions of a live teaching process, infused with voice, intention, and often the energy of a real classroom.

Moreover, the design avoids overwhelming students with options. Each course is presented with:

- A clear title and description;
- Estimated time for completion;
- A featured image for visual identity;

- Course preview clips where available;
- Course Quizzes to test students progress;
- Guiding Materials as PDF files;
- Optional certification upon completion.

In short, *RAU Academy Education* reflects a commitment to **accessibility without dilution, structure without rigidity, and technology without dehumanization**. It was designed not as a replacement for university teaching, but as its **evolutionary complement**—a way to translate the richness of academic discourse into a format that meets the contemporary learner where they are.

4. Advantages for Learners

One of the central ambitions behind *RAU Academy Education* was to address the evolving needs of contemporary learners—students who are no longer passive recipients of knowledge but active agents in their own educational journey [3]. The platform was thus crafted to offer **convenience, autonomy, and quality**, aligning with global trends in learner-centered pedagogy.

4.1. Flexibility and Accessibility

Today's students lead increasingly complex lives, often balancing academic work with part-time jobs, internships, family responsibilities, or personal development activities. As such, **asynchronous access** to academic content becomes not a luxury, but a necessity.

RAU Academy Education allows students to:

- Access courses **anytime, from any device** with internet connectivity;
- Rewatch complex explanations or demonstrations;
- **Pause, rewind, or fast-forward** through lectures at their own pace;
- Learn in both **Romanian and English**, depending on the course.

This flexibility supports diverse learning rhythms and offers a **personalized study pace**, especially valuable for students who need more time to internalize abstract or technical concepts.

4.2. Complement to Live Teaching

Rather than replacing face-to-face teaching, the platform acts as a **pedagogical extension** of the university classroom. Courses are often recorded during real teaching sessions or based on the same material, allowing students to:

- Reinforce knowledge gained during synchronous lectures;
- Catch up on missed sessions;
- Prepare ahead for exams or projects.

This hybridization of teaching methods supports what many universities now refer to as **blended learning**, where digital resources supplement but do not substitute physical presence and interaction.

4.3. Quality and Clarity of Content

Courses uploaded to *RAU Academy Education* follow a minimum standard in terms of:

- **Length** (minimum 2.5 hours of total video content);
- **Clarity** of structure (modules, subchapters);
- **Professional editing** where needed;
- **Visual branding and navigation aids.**

These quality controls ensure that students receive a consistent experience and that the **pedagogical value of each course is preserved**—even when accessed independently, outside of traditional class times.

Moreover, recorded video can allow for **more careful listening** than real-time lectures. Students can pause to take notes, reflect on examples, and absorb theoretical explanations at their own cognitive pace.

4.4. Additional Certifications and Lifelong Learning

Several courses offer optional **certification upon completion**, providing students with proof of additional learning beyond the formal curriculum. This feature:

- Encourages the development of **extra-academic skills**;
- Motivates continuous learning;
- Supports students in building **a portfolio of micro-credentials.**

This aligns with international shifts toward **modular education**, where learners assemble diverse qualifications over time in response to rapidly changing job market demands.

5. Benefits for Faculty Members

While most digital learning platforms focus primarily on enhancing the student experience, *RAU Academy Education* was consciously designed to also serve the academic staff—empowering them to **extend their reach, refine their teaching style, and gain professional recognition**, while also offering tangible incentives for their contributions [2].

5.1. Academic Visibility and Recognition

By recording and publishing video courses, professors become **more visible within the university ecosystem**, but also **beyond institutional boundaries**. A well-structured and professionally edited course allows educators to:

- Present their **personal teaching style and intellectual voice**;
- Be discovered by potential collaborators, researchers, or students from other institutions;
- Share their **expertise with the wider public**, thereby increasing the university's visibility and academic impact.

In a world where digital presence contributes increasingly to professional profiles, recorded video courses become **digital assets** of intellectual value.

5.2. Financial Incentive

To further support and encourage content creation, *RAU Academy Education* offers a **revenue share** from the sale of any course created and uploaded by the professor. Additionally, for initial participation, professors receive a **fixed bonus** for any course that meets the minimum standard (minimum 2.5 hours of content, properly structured and edited).

This revenue-sharing model acknowledges the **value of intellectual property and teaching effort**, offering professors an alternative source of income while supporting the university's mission. Moreover, the financial incentive model creates a sustainable ecosystem that rewards educational innovation. As highlighted by Bates [1], *digital pedagogy flourishes when teachers are treated as co-creators, not merely content providers*.

5.3. Support with Technical Production

Many faculty members feel hesitant about recording video courses due to:

- Lack of technical experience;
- Camera anxiety;
- Uncertainty about video editing or formatting.

To address these concerns, the university offers **complete production support**:

- Video recordings can be made during live Microsoft Teams lectures;
- Professors can opt to record in a **dedicated space**, assisted by the platform team;
- All **post-production editing** is handled centrally;
- Professors only need to **focus on teaching**—the rest is taken care of.

This removes a significant barrier and encourages participation by making the process **accessible and non-intimidating**.

5.4. Contribution to Modernizing the Educational Ecosystem

Participation in *RAU Academy Education* offers faculty members the opportunity to be part of **an educational shift**:

- From traditional teaching to hybrid learning;
- From fixed schedules to flexible, student-driven access;
- From localized classrooms to potentially **global audiences**.

This aligns with the mission of modern universities to remain **adaptive, innovative, and relevant**—qualities especially critical in a time of rapid technological change and student mobility.

5.5. Pedagogical Innovation and Legacy

Recorded courses provide professors with a tool for **self-evaluation and pedagogical refinement**:

- Watching oneself teach can reveal patterns, pacing issues, or areas of improvement;

- Structuring a course for online format often leads to **clearer learning outcomes** and better modular organization;
- Courses remain available for years, allowing for **updates, iterations, and improvement** over time.

Finally, faculty members contribute to building a **long-term educational legacy**, ensuring that their knowledge and teaching efforts continue to benefit learners for generations to come—even beyond the limits of a single semester or classroom.

6. Implementation Challenges

Despite the promising vision and strategic design behind *RAU Academy Education*, the journey from concept to implementation has been marked by a series of **multi-layered challenges**. These difficulties reflect the realities of digital transformation in higher education, where **technology, human behavior, institutional culture, and pedagogical paradigms** intersect [3].

6.1. Faculty Reluctance and Cultural Resistance

Perhaps the most significant challenge has been **motivating professors to actively participate** in the creation of video-based courses. Multiple underlying factors contribute to this reluctance:

- **Camera anxiety** and discomfort with being recorded;
- A perceived **lack of time** or misalignment with existing teaching responsibilities;
- Fear of judgment or exposure in a new medium;
- Skepticism about the long-term benefits of recorded lectures;
- A **lack of digital teaching habits**, especially among senior faculty.

Although the platform offered training, technical support, and even financial incentives, adoption has remained **gradual and uneven**, requiring continued efforts in **community building, peer advocacy, and internal storytelling**.

6.2. Time Investment and Workload

Creating a high-quality course—especially one that is asynchronous and professionally edited—requires a **non-trivial investment of time**:

- Preparing structured content;
- Ensuring clarity and conciseness for on-camera delivery;
- Revisiting and adapting traditional lecture materials to suit a modular, digital format.

Even with support, many faculty members perceive this as **an added workload** on top of their teaching and research duties. Balancing quality expectations with available time remains an ongoing concern.

6.3. Perceived Value of Digital Instruction

Another barrier has been the **perception that live, in-person teaching is inherently superior** to digital formats. Some professors hesitate to translate their courses to video, fearing that:

- **Depth and nuance may be lost** in a digital format;
- Student engagement may decline without real-time interaction;
- Their personal teaching style may not be adequately conveyed through a screen.

These concerns are valid and require **pedagogical dialogue** and exposure to global trends in hybrid learning, where digital content **complements**, rather than replaces, live teaching.

6.4. Platform Usability and Technical Expectations

The design of *RAU Academy Education* prioritized accessibility and multilingual support, but **technical expectations** still exist:

- Professors unfamiliar with digital tools sometimes require extensive onboarding;
- Uploading content, structuring modules, and adjusting metadata require **digital literacy** and procedural clarity;
- Occasional bugs or delays in processing can erode trust in the platform's reliability.

Regular updates, **clear documentation**, and responsive technical support have helped reduce friction, but **change management remains essential**.

6.5. Legal and Ethical Considerations

As with any initiative involving the **recording and distribution of educational content**, legal and ethical issues must be navigated:

- **Copyrights and content ownership** need to be clarified;
- **Consent for student appearances** in live recordings must be managed;
- Ensuring **GDPR compliance** for video hosting and data collection is essential;
- Professors must be assured of the **non-exclusive use of their materials**, with the right to reuse or republish them elsewhere.

These dimensions require **transparent agreements**, trust-building, and close collaboration with the university's legal and administrative teams.

7. Opportunities for Students

One of the central aims of the *RAU Academy Education* platform is to **empower students** through increased flexibility, access to quality content, and new formats of engagement. In the context of rapid technological evolution and shifting student expectations, the benefits offered to learners are both immediate and long-term.

7.1. Flexible Learning Paths

Unlike traditional in-class teaching, which is **bound by rigid schedules and physical presence**, the platform allows students to:

- Access content **anytime and anywhere**, accommodating different learning paces and time zones;
- Review materials **multiple times**, which is particularly helpful for complex topics;
- Integrate learning into **personalized study routines**, increasing retention and autonomy.

This **asynchronous model** helps support **working students, international students**, and those with non-traditional learning styles.

7.2. High-Quality and Structured Content

Each course uploaded to the platform is:

- **Curated and edited**, ensuring a clear, concise, and coherent presentation;

- Accompanied by **additional resources** such as quizzes, slides, readings, or external links;
- Presented in **modular form**, enabling students to track their progress and focus on specific areas of interest.

Such consistency increases **perceived value** and allows learners to engage with the material at a deeper level.

7.3. Multilingual Access

The platform's **multilingual interface** (Romanian and English) expands its reach and usability:

- Romanian students benefit from native-language materials;
- International students or exchange participants can **follow English-based courses**;
- The possibility to create **parallel content in both languages** supports broader academic inclusion.

This aligns with the **international mission** of the Romanian-American University and prepares students for cross-cultural communication.

7.4. Development of Digital Learning Skills

Navigating the RAU Academy platform fosters essential **21st-century skills**, such as:

- Self-directed learning;
- Information literacy;
- Familiarity with educational technology environments;
- Capacity for **lifelong, autonomous learning**.

These competencies are indispensable in a knowledge economy shaped by continuous change and **AI integration**.

7.5. Access to a Growing Library of Courses

As the platform grows, students gain access to:

- A **wide spectrum of subjects** from various faculties;

- Courses created by professors with **real-world experience**;
- The possibility to **cross-register** or explore other disciplines at their own pace.

This **interdisciplinary access** enhances holistic understanding and may stimulate new academic or career interests.

7.6. Continuity Beyond Graduation

A longer-term vision of the platform involves its **integration into lifelong learning strategies**:

- Alumni may retain access to selected materials;
- Professionals can return to update their knowledge;
- Specialized courses can be offered to the public, connecting the university with wider audiences.

Students benefit from flexible access, multilingual materials, and additional certification opportunities.

The RAU Academy model illustrates how **digital learning can enhance—not diminish—the sense of academic belonging**, a point frequently discussed in *Pedagogies of Digital Learning in Higher Education* [5].

Such continuity reinforces the idea of **university as a lifelong companion**, not just a temporary institution.

8. Benefits for Professors

In the evolving landscape of digital education, *RAU Academy Education* presents **meaningful advantages** for professors who choose to engage with the platform. Beyond institutional visibility, the platform offers new pedagogical, professional, and even financial benefits that align with modern academic expectations.

8.1. Enhanced Pedagogical Impact

By designing recorded video courses, professors are encouraged to:

- **Structure content more clearly and effectively**, which often leads to improved clarity in both recorded and live teaching;
- Focus on **learning outcomes** and instructional coherence;

- Incorporate **multimedia elements** to enhance conceptual understanding.

This reflective process supports **teaching innovation** and academic excellence.

8.2. Extended Reach and Academic Visibility

The platform allows professors to:

- Reach students **beyond the physical classroom**, including those in other faculties, universities, or countries;
- Promote their expertise and **personal academic brand**;
- Gain recognition for their **contributions to digital education** within and beyond RAU.

Such visibility may lead to **new collaborations, invitations, and citations**, contributing to academic reputation.

8.3. Asynchronous Teaching Efficiency

Once a course is recorded and uploaded:

- Professors save time on **repetitive explanations** of core concepts;
- They can focus live sessions on **interaction, case studies, and student feedback**;
- Course delivery becomes more **scalable and sustainable** over time.

This balance supports a **hybrid teaching model** where video complements real-time engagement.

8.4. Continuous Improvement and Peer Learning

The recording process invites professors to:

- Reflect on **teaching methods and presentation style**;
- **Iterate and update** content between semesters with minimal effort;
- Engage in **peer-exchange** by viewing how colleagues structure and deliver their courses.

This fosters a **community of practice** that raises the quality of teaching across the university.

8.5. Financial Incentives and Ownership

To further motivate participation:

- Professors receive **financial compensation**;
- Additionally, they receive **percentage of the net revenue** generated by their course's sales on the platform;
- Importantly, the **intellectual property rights remain non-exclusive**, allowing professors to reuse and repurpose their materials as they wish.

This model recognizes the **intellectual effort** invested and **rewards initiative and creativity**.

8.6. Contribution to the University's Modernization

By contributing to the platform, professors:

- **Support the university's strategic transition** toward blended and lifelong learning;
- Help develop a **repository of high-quality educational content**;
- Play an active role in **adapting higher education to digital expectations**.

Professors gain visibility, confidence, and recognition for their digital contributions. Recorded lectures become intellectual assets that extend their pedagogical reach and build a lasting academic legacy [4].

This participatory approach cultivates a sense of **ownership, pride, and institutional alignment**.

9. Technical and Logistical Challenges

While the *RAU Academy Education* platform brings significant promise, its implementation is not without **complexities and limitations**. Understanding these challenges is essential for creating realistic expectations, optimizing workflows, and ensuring long-term success. These challenges can be grouped into three major categories: technical infrastructure, content production logistics, and adoption resistance.

9.1. Infrastructure and Platform Stability

Building a scalable and secure e-learning environment requires:

- **Robust servers and reliable uptime**, especially under high-traffic conditions (e.g., exam periods);
- **Responsive design** to support various devices (desktop, mobile, tablet);
- **Data privacy compliance**, particularly with GDPR, including secure user authentication and encrypted payment gateways;
- Periodic **platform maintenance and updates** to ensure compatibility with new technologies.

Even with external hosting providers, **cost and technical oversight** remain ongoing concerns that require careful budgeting and IT coordination.

9.2. Content Production and Post-Processing

One of the most significant logistical barriers has been the **filming and editing of video lectures**. Challenges include:

- Professors' **reluctance or discomfort with being recorded**, due to public exposure, self-criticism, or lack of technical confidence;
- **Time constraints**, as many faculty members already have full teaching loads;
- Need for **professional equipment, filming locations, and post-production capacity**;
- Ensuring **pedagogical quality**—not just “talking head” videos, but structured, engaging lessons with appropriate visuals.

A dedicated support team for video recording, editing, and instructional design has proven crucial to lowering this barrier.

9.3. Platform Adoption and Change Resistance

Despite communication efforts and incentives, **many professors hesitate** to join the platform due to:

- **Perceived lack of immediate benefit** or alignment with their traditional teaching methods;
- Uncertainty about how the platform **fits into their workload** or evaluation metrics;
- Concerns about **loss of control** over their teaching materials;
- General resistance to adopting **new technologies** without formal training or institutional pressure.

To overcome this, we observed the need for:

- **Ongoing training and coaching sessions;**
- **Public recognition and rewards** for early adopters;
- Transparent communication about **rights, royalties, and responsibilities;**
- Creating a sense of **collective purpose**, rooted in the university's modernization vision.

9.4. Multilingual Content and Standardization

The platform's bilingual nature (Romanian and English) introduces:

- The need for **language-specific versions of courses**, not merely translations;
- Challenges in ensuring **terminological consistency** across courses and faculties;
- Additional effort from instructors in **course duplication or parallel planning;**
- A lack of unified video standards across different departments, leading to **varying quality and structure.**

To address this, we introduced **guides and templates**, and encouraged shared best practices between content creators.

9.5. Integration with Existing Educational Processes

A frequent question raised was:

“How does this platform integrate with existing teaching obligations?”

Because the platform initially runs **parallel** to standard courses, faculty needed to be reassured that:

- Participation is **optional and flexible**, not compulsory;
- The platform **complements** in-class or Teams-based teaching, not replaces it;
- It serves as an **archive, a resource, and a showcase**, particularly for new audiences, alumni, or lifelong learners.

Like any institutional platform, RAU Academy Education requires ongoing adaptation—both in infrastructure and in human support systems. As Smith (2023) argues, digital transformation is a **continuous ecosystemic process, not a one-time technological event** [2].

Integration efforts are ongoing, with future plans to **embed platform materials directly** into LMS tools and academic workflows.

10. Lessons Learned and Recommendations

The development and partial implementation of *RAU Academy Education* has provided a fertile ground for understanding the **dynamics of educational innovation** in a traditional academic setting. From initial ideation to the current operational phase, the project has yielded valuable insights—both encouraging and cautionary. These lessons can help refine future iterations and inform similar initiatives in other academic environments.

10.1. Key Takeaways

a. Motivation Requires Multiple Layers

Intrinsic motivation (passion for teaching, academic pride) is not always sufficient to drive adoption. Professors also need:

- Clear **extrinsic motivators** (e.g., financial rewards, visibility, certificates);
- **Recognition** from institutional leadership;
- A feeling of **community and shared purpose** with peers on the platform.

b. Simplicity Enables Participation

The more frictionless the process, the higher the likelihood of participation. Providing:

- **Recording support** (camera, editing, scripting);
- **Templates and checklists** for course planning;
- **Guided onboarding** reduces resistance and increases confidence.

c. Early Adopters Are Catalysts

The involvement of a few enthusiastic faculty members helped:

- Demonstrate feasibility;
- Serve as ambassadors;
- Create momentum within departments.

Their involvement also validated the platform's legitimacy in the eyes of others.

c. Technical Quality Matters—But Not Above All

While clean visuals and sound are important, what truly matters is:

- **Clarity of explanation;**
- **Logical course structure;**
- Authenticity of delivery.

Students respond more to relevance and clarity than cinematic polish.

d. Flexibility Ensures Scalability

Allowing for different types of courses (seminars, lectures, tutorials), lengths, and formats:

- Enables more teachers to participate;
- Encourages **experimentation;**
- Supports **varied learner needs.**

A rigid format would have discouraged broader participation.

10.2. Strategic Recommendations

For Universities:

- **Integrate asynchronous platforms** within the curriculum strategically, not just as add-ons.
- Consider establishing **centers for digital teaching excellence**, offering full-cycle support from design to post-production.
- Provide **academic credits or evaluation advantages** for course authorship.

For Instructors:

- Think of your video course as a **legacy and digital extension** of your academic identity.
- Use the platform as a **sandbox for pedagogical innovation**—trying new structures, storytelling techniques, or formats.
- Collaborate with peers across disciplines to create **interdisciplinary modules**.

For Platform Developers:

- Embed **feedback loops** from students and faculty into the platform interface;
- Allow for **modular course building**, versioning, and multi-language support;
- Incorporate **analytics and performance dashboards** to track engagement and impact.

10.3. Toward a Sustainable Educational Ecosystem

As global education transitions toward hybrid and post-digital paradigms, initiatives like *RAU Academy Education* are not merely technological upgrades—they represent a deeper shift in **how we understand knowledge transmission**.

The long-term success of such platforms depends on:

- **Authentic faculty involvement;**
- **Iterative design and adaptation;**
- Alignment with the university's mission to **educate ethically, creatively, and inclusively**.

The journey of developing *RAU Academy Education* has shown that educational innovation thrives when technology, authenticity, and institutional vision converge. True success lies not merely in technical excellence, but in cultivating a digital culture that values collaboration, creativity, and ethical pedagogy [1].

This platform, born from necessity and vision, is a microcosm of a larger transformation. It challenges traditional norms while reaffirming the timeless role of the educator—now, in dialogue with the screen, the algorithm, and the world.

11. Conclusions

The process of designing and implementing the *RAU Academy Education* platform has been both an ambitious endeavor and a revealing case study in the intersection between **digital**

transformation and academic tradition. The experience of this project—carried out within a well-established Romanian university—sheds light on the **tensions, aspirations, and structural dynamics** of 21st-century higher education.

11.1. Challenges: Cultural, Structural, and Psychological

Despite the evident benefits of e-learning platforms, the **main obstacle was not technological**—but rather **human**.

- **Cultural resistance** within academia proved to be significant. Professors were reluctant to expose themselves on camera, unsure of their digital presentation skills, or skeptical about the pedagogical value of asynchronous content.
- The **lack of institutional obligation** to participate meant that adoption depended exclusively on intrinsic motivation and persuasive communication. In a system accustomed to traditional incentives and academic rhythms, this required a recalibration of expectations and strategies.
- There was a recurring sense of "**digital intimidation**": even seasoned educators felt vulnerable when faced with unfamiliar recording processes, performance anxiety, or concerns about content visibility beyond the classroom.

Moreover, **time constraints** and already overloaded academic schedules posed real barriers, making it difficult for even well-intentioned faculty to engage with the project without structured support.

11.2. Results: Emergent Successes and Systemic Learnings

Despite these challenges, the platform succeeded in **building momentum**:

- A core group of professors accepted the challenge, and their recorded courses became **model exemplars** for others.
- The **multilingual interface** and the openness to both Romanian and English content positioned the platform as a tool for internationalization, not just digitization.
- Students responded positively to the idea of having **on-demand access to faculty-led courses**, especially for revision, asynchronous study, or bridging learning gaps.

Most importantly, the project generated a **new institutional narrative**: one that recognizes **pedagogical innovation** as a shared responsibility and **digital tools** as means for preserving—not replacing—the human element in education.

Through careful iteration, open dialogue, and adaptive leadership, the platform evolved from being a **technological experiment** to a **strategic pillar** of the university's vision for the future.

11.3. The Way Forward: E-learning as a Strategic Ecosystem

The main conclusion is clear: building an academic e-learning platform is **not just about infrastructure—it is about culture**.

True adoption requires:

- **Trust**—in the process, in the leadership, and in one's own ability to adapt.
- **Support systems**—from technical assistance to editorial and recording help.
- **Incentive structures**—that reward creativity, initiative, and openness.

More broadly, the case of *RAU Academy Education* offers a replicable framework for other universities facing similar transitions. It underscores the need to view educational platforms not merely as repositories of content but as **ecosystems for intellectual exchange**, professional growth, and institutional renewal.

The case of RAU Academy Education demonstrates that **the challenge of digital transformation is primarily cultural, not technical** [3]. By addressing fears, building trust, and fostering intrinsic motivation, the university laid the foundation for a sustainable educational ecosystem.

RAU Academy Education is not just a repository of recorded lectures—it is a living, evolving expression of the university's mission: to teach with authenticity, adapt with integrity, and innovate with purpose.

In a world where education is increasingly **borderless, digital, and self-paced**, universities that embrace **authentic digital transformation**—without compromising their pedagogical identity—will emerge as leaders in shaping the next generation of learners.

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THE DIGITAL RESONANCE PARADIGM: REFRAMING INFORMATION AND COMMUNICATION TECHNOLOGIES AS COGNITIVE-EMOTIONAL SYSTEMS OF COHERENCE

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Abstract

In an era where digital transformation defines organisational evolution, technology has shifted from a functional infrastructure to a cognitive-emotional medium of human experience. The Digital Resonance Paradigm is a theoretical model that posits the future of Information and Communication Technologies (ICT) depends on attunement rather than automation. Attunement is defined as the alignment between technological intelligence and human sensibility. Drawing on service-dominant logic, emotional design, and systems theory, the framework identifies four interacting dimensions: technological frequency, cognitive resonance, emotional resonance, and value coherence. Through these, meaning, trust, and experiential harmony arise. The study reframes ICT as a co-creative participant in value formation, transforming service systems into adaptive environments of empathy and coherence. By advancing Digital Resonance as a new paradigm of innovation, it calls for technologies that no longer compete with consciousness but resonate with it. This restores equilibrium between data, design, and the human spirit..

Keywords: Digital Transformation, ICT, Artificial Intelligence, Behavioural Science, Tourism, Industry 4.0.

JEL Classification: D91, L86, M31, Z32.

1. Introduction

The fast merging of Information and Communication Technologies (ICT) and human experience has changed how value is created today. In many industries, such as tourism and services, technology now acts as an active interface for cognition, perception, and emotion rather than being a neutral tool. Digital ecosystems are advancing rapidly, artificial intelligence is advancing, and the physical and virtual worlds are blending. As a result, organisations are rethinking their strategies and the goals of digital transformation [1].

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This conceptual paper introduces the **Digital Resonance Framework**, a theoretical model that reconceptualizes information and communication technology (ICT) as a cognitive and emotional infrastructure. The framework aligns technological intelligence with human sensibility. The subsequent phase of digital transformation moves beyond automation and efficiency, prioritizing alignment as the ability of systems to correspond with users' cognitive processes, emotional states, and ethical standards [2]. Through this lens, ICT emerges as a medium of coherence: a dynamic equilibrium between data and design, performance and perception, machine logic and human meaning.

Recently, digital transformation discourse has shifted from infrastructure to strategic and behavioural integration. However, emotional and experiential aspects remain under-theorised. Scholars in service innovation, experience design, and systems thinking emphasize interaction, alignment, and adaptation as key to value creation, yet a unified digital framework remains missing. This paper aims to address that gap.

Key Contributions

This paper offers three main contributions to the literature on Information and Communication Technologies (ICT), digital transformation, and service innovation:

I. Conceptual Reframing of ICT as Cognitive–Emotional Infrastructure

The study introduces the *Digital Resonance Framework*, positioning ICT not merely as a technical enabler but as a dynamic medium of cognitive and affective alignment. This reframing extends the digital transformation discourse toward psychological and experiential dimensions of technological design.

II. Integration of Disparate Theoretical Traditions into a Unified Logic of Coherence

By synthesising service-dominant logic, emotional design, and systems thinking, the paper establishes a multi-level conceptual bridge connecting information systems theory with cognitive science and aesthetics, offering a new lexicon for understanding human-technology attunement.

III. Proposal of a Resonance-Based Paradigm for Future ICT Research and Practice

The framework identifies four interdependent dimensions: technological frequency, cognitive resonance, emotional resonance, and value coherence. These dimensions enable digital ecosystems to achieve adaptive harmony. This paradigm shifts the focus of innovation from automation to *attunement*, thereby redefining performance in terms of experiential coherence and ethical design.

Literature Review

I. ICT and Digital Transformation

The digital transformation of contemporary economies has progressed beyond operational improvements to become a structural revolution that redefines value creation, perception, and sustainability. Information and Communication Technologies (ICT) play a pivotal role in this transformation by enabling automation, facilitating data exchange, and acting as systemic catalysts. This process fundamentally transforms the ontological foundations of organisational behaviour. Bharadwaj [3] introduced the concept of *digital business strategy*, contending that the integration of information and communication technology (ICT) extends beyond technical alignment and functions as a primary source of strategic differentiation. Vial [4] further develops this perspective, defining digital transformation as a process that restructures the interdependencies among technology, organisation, and environment.

Within tourism, information and communication technology (ICT) not only digitises traditional operations but also fundamentally transforms the delivery of experiences. Kane et al. [5] contend that digital transformation is driven chiefly by an organisation's capacity to reinterpret customer value through innovative digital frameworks, rather than by technological novelty alone. Li conceptualises [6] this shift as a reconfiguration of business models, where data flows, algorithmic mediation, and networked interactions become the primary drivers of creativity and differentiation. As a result, information and communication technology (ICT) evolves from a functional subsystem into a **cognitive architecture**. Thus, it shapes user perception and engagement within service environments.

What emerges from this literature is a consensus that digital transformation requires a cultural and epistemological shift: from viewing ICT as infrastructure to perceiving it as *intelligence in motion*. Reis et al. [7] propose that this evolution poses new challenges for researchers, chiefly the need to understand how technological systems interact with human cognition to create adaptive, self-sustaining ecosystems of value.

II. Service Innovation and the Experience Economy

The focus of service innovation has transitioned from optimizing tangible performance metrics to orchestrating experiential meaning. Pine and Gilmore [8] defined this shift as the *Experience Economy*, a paradigm in which value is derived from engagement and emotion rather than product ownership. Vargo and Lusch [9] expanded upon this perspective by introducing *Service-Dominant Logic*, which asserts that value is generated through dynamic interactions between providers and consumers, rather than through unilateral production.

Within this framework, digital technologies improve the effectiveness of interactions and co-creation between service providers and consumers. Ostrom et al. [10] identify information and communication technology (ICT) as a mechanism that enables service research to respond to societal turbulence and changing expectations. Edvardsson et al. [11]

further argue that service systems should be analysed as evolving constellations of value co-production, capable of continuous learning and adaptation.

In the tourism sector, this perspective redefines the role of the service provider, shifting focus from logistical facilitation to the curation of emotional experiences-effectively becoming an *emotional curator*. Zeithaml et al. [12] observe that customers increasingly differentiate experiences based on perceived authenticity and emotional quality, rather than price or efficiency. Consequently, experience functions as a symbolic currency, exchanged through digital channels that foster connection, self-expression, and belonging.

III. Smart Tourism Ecosystems

The convergence of ICT and service innovation culminates in what Buhalis and Amaranggana describe as the *Smart Tourism Destination*: a synergistic network where data, connectivity, and user participation coalesce to create adaptive, context-aware experiences [13]. Gretzel et al. [14] position smart tourism as the natural evolution of ICT-enhanced ecosystems, structures capable of sensing, learning, and responding to user behaviour in real time.

In smart systems, information functions as a dynamic resource that circulates among stakeholders. Neuhofer et al. [15] argue that technology improves the tourism experience by facilitating co-creation at various touchpoints and by merging physical and digital environments to create hybrid experiential spaces. Mariani et al. [16] situate this evolution within the Industry 4.0 paradigm, defining smart systems as socio-technical assemblages that continuously adapt to user input to enhance service quality.

The literature identifies the digital ecosystem as a manifestation of collective intelligence, an adaptive environment in which human and artificial agents collaborate to create personalised, seamless experiences. Xiang and Fesenmaier argue that Big-Data analytics serves as the primary processing mechanism in these ecosystems, enabling tourism organizations to analyze complex behavioral data and develop targeted interventions [17]. Nevertheless, although the smart-tourism paradigm effectively addresses technological integration and operational intelligence, it offers limited insight into the *affective* dimension of these interactions, specifically how technological systems influence the emotional and cognitive aspects of user experience.

IV. Emotional and Cognitive Experience Design

Alongside the digital transformation of services, a significant research trajectory within human-computer interaction and design studies examines the mediating role of emotion in technological experience. Norman introduced the principle of *emotional design* [18], demonstrating that aesthetic pleasure and affective connection substantially influence usability and satisfaction. Desmet and Hekkert expanded upon this argument by proposing the *Framework of Product Experience* [19], which identifies sensory, emotional, and meaning-driven components as essential to technology acceptance.

McCarthy and Wright [20] reconceptualized technology as experience, contending that digital artefacts function as emotional mediators that shape perception and memory. Hassenzahl introduced experience design as the deliberate creation of meaning and pleasure, emphasizing that technology ought to evoke feelings of beauty, control, and flow [21]. Tractinsky further emphasized the aesthetic aspect by linking visual harmony and affective response to cognitive fluency and user trust [22].

Applied to ICT-enabled services, these theoretical perspectives indicate that emotion functions as both an input and an output within digital systems. Davenport and Ronanki contend that artificial intelligence translates emotional cues into actionable insights, enabling adaptive systems to respond effectively to user behavior and mood [23]. Huang and Rust [24] and Dwivedi et al. [25] extend this conversation by positioning AI as an emotional co-actor. This is an intelligent layer capable of interpreting human sentiment and adjusting system behaviour accordingly.

Despite these advancements, a clear theoretical gap persists. Current literature treats emotion either as a design consideration or as an outcome variable. There is rarely an organising principle of technological ecosystems. The field lacks a unified vocabulary to describe how digital infrastructures resonate with human cognition and feeling, how *frequency* in the informational sense translates into *affect* in the experiential sense.

V. Synthesis and Research Gap

Across these converging literatures, digital transformation, service innovation, smart ecosystems, and emotional design, a single pattern emerges: technology's evolution toward experiential intelligence. Yet, the theoretical frameworks underpinning these domains remain largely disjointed. Digital-transformation studies emphasise structural adaptation; service-innovation models focus on value co-creation; design research explores affective engagement. What remains under-theorised is the *integrative mechanism* through which these domains interact to produce meaning and emotional coherence.

This conceptual lacuna invites a new theoretical construct, **Digital Resonance**, that unites these strands under a shared logic of alignment. Digital Resonance captures the process by which ICT systems and human users achieve dynamic harmony, translating data-driven intelligence into emotional and cognitive coherence. In this sense, it reframes ICT from a vehicle of information transfer into a medium of experiential synchronisation.

The existing literature provides the necessary scaffolding for this synthesis:

- From Vial and Kane et al. comes the recognition that digital transformation redefines strategic logics [4][5].
- From Vargo and Lusch arises the understanding that value is co-created through relational processes [9].

- From Norman [18], Desmet and Hekkert [19], and Hassenzahl [21], emotion and aesthetics constitute measurable dimensions of technological success.
- From Buhalis and Amaranggana [13] and Gretzel et al. [14], we derive the context of tourism as a fertile ground for such an integrative theory.

Together, these works underscore the need to move beyond efficiency-driven innovation toward resonance-driven transformation. In the evolving digital landscape, where the boundaries between intelligence and intimacy blur, the next phase of research must ask not *what* technology does, but *how it feels to use it*. Even more, *why that feeling matters for the future of service innovation*.

2. Conceptual Framework: The Digital Resonance Model

The contemporary digital ecosystem serves as both a technical infrastructure and a dynamic communicative environment, enabling ongoing interactions among data, emotion, and cognition. In this context, Information and Communication Technologies (ICT) shape human experience by converting computational logic into emotional processes. To understand how technology transcends its instrumental role and becomes a source of meaning, this study proposes a theoretical construct termed Digital Resonance.

2.1 Defining Digital Resonance

Digital Resonance is defined as the dynamic alignment between the cognitive-emotional frequencies of human experience and the adaptive intelligence of information and communication technology (ICT) systems. This concept describes the moment when technology and users achieve a shared rhythm of understanding, resulting in a synchronization where the system operates efficiently and feels intuitively appropriate.

In contrast to conventional models that regard usability or satisfaction as outcomes of interaction, Digital Resonance conceptualizes these qualities as emergent harmonies within a continuous feedback loop between human and machine. This framework asserts that both the user and the system engage in a collaboratively constructed process involving perception, adaptation, and the development of affective coherence.

In the context of tourism, digital resonance refers to the ability of digital systems to anticipate user needs, provide contextually relevant content, and maintain aesthetic consistency. Thereby, collectively enhancing trust and user satisfaction. A recommendation engine that adapts its tone and visuals to a traveler's emotional state, or an AI assistant that learns to respond with empathic nuance, exemplifies this principle in practice.

2.2 Theoretical Foundations

The construct of Digital Resonance synthesises insights from four major theoretical traditions: **service-dominant logic**, **experience design**, **cognitive resonance theory**, and **systems thinking**.

a. Service-Dominant Logic

Vargo and Lusch's *Service-Dominant Logic* reframes value creation as a collaborative, interactive process in which both provider and consumer act as co-producers of meaning [9]. In this view, services are platforms for *value co-creation*, not mere exchanges of utility. Digital Resonance extends this principle to the human-technology relationship, suggesting that ICT systems themselves become co-creators of value by attuning their functionality to the user's affective and cognitive rhythms.

b. Experience Design and Emotional Cognition

Drawing upon Norman's *emotional design* [18] and Hassenzahl's *experience design* [21], the concept of Digital Resonance asserts that pleasure, aesthetics, and perceived empathy are essential components of technological acceptance. Desmet and Hekkert's framework of product experience, encompassing sensory, affective, and symbolic dimensions, serves as a foundation for conceptualizing resonance as an emergent property of human–technology interaction [19].

c. Cognitive Resonance

Borrowed metaphorically from neuroscience, *cognitive resonance* describes the synchronisation of neural oscillations that underlie coherent perception and decision-making. In a digital environment, this concept illuminates how alignment between user expectation and system behaviour generates cognitive fluency. This is a mental ease feeling that fosters engagement and trust.

d. Systems Thinking

Finally, systems thinking situates ICT ecosystems as adaptive, feedback-driven entities that continuously evolve through their interactions with the environment. From this perspective, Digital Resonance represents the *homeostatic equilibrium* of such systems. This becomes a state where technological adaptability and human sensibility mutually stabilise one another.

2.3 The Dimensions of Digital Resonance

Digital Resonance is conceptualised as a four-dimensional construct encompassing **technological frequency**, **cognitive resonance**, **emotional resonance**, and **value coherence**.

Each dimension represents a unique interface between system intelligence and human experience.

Dimension	Definition	Illustrative Example (Tourism Context)
Technological Frequency	The degree to which ICT systems dynamically adapt to user input through real-time data processing, interactivity, and responsiveness.	A tourism platform that modifies itinerary recommendations in response to live user sentiment or environmental changes.
Cognitive Resonance	The sense of alignment between user expectations and system logic; the perception that the system “understands” the user’s mental model.	A booking interface that intuitively anticipates search patterns, reducing decision fatigue.
Emotional Resonance	The affective harmony produced when system aesthetics, tone, and behaviour align with the user’s mood and values.	An AI assistant that mirrors a traveller’s excitement or calm through adaptive language and imagery.
Value Coherence	The integrative perception that the digital experience simultaneously satisfies practical, cognitive, and emotional needs.	A seamless cross-platform experience where content, design, and communication feel consistently meaningful.

Table 1. Dimensions of system intelligence and human experience in tourism context.

Collectively, these dimensions illustrate that resonance emerges not as a static property but as an evolving pattern of synchronisation. Therefore, resonance can be understood as a continuous negotiation between human sensibility and system adaptability.

2.4 Conceptual Propositions

From this theoretical synthesis, three conceptual propositions emerge:

- **P1: ICT capability acts as a catalyst for emotional resonance** by enabling personalisation, responsiveness, and interactivity that evoke affective engagement.

- **P2: Emotional resonance mediates the relationship between technological capability and perceived service quality**, as users interpret technological fluency through the lens of emotional satisfaction.
- **P3: Value coherence is the emergent outcome of sustained digital resonance**, in which technological and emotional alignment converge to generate loyalty, trust, and memory.

These propositions are not hypotheses to be empirically tested but *conceptual bridges* linking the disparate literatures of digital transformation, service innovation, and affective design into a unified logic of alignment.

2.5 Implications of the Framework

The Digital Resonance Framework repositions ICT as a **cognitive-emotional infrastructure** rather than a functional subsystem. In tourism and related industries, this shift holds profound implications. This perspective suggests that innovation is now characterized less by the speed or efficiency of information exchange and more by the degree of *alignment* between technological adaptive intelligence and the user's emotional state. When systems achieve such resonance, they move beyond a purely utilitarian function and enter the domain of empathy, focusing on understanding rather than mere usability.

Moreover, this framework reframes the managerial conception of digital value creation. Instead of optimising isolated performance metrics, organisations should design for coherence, ensuring that every layer of digital engagement, from interface aesthetics to algorithmic decision rules, operates in harmonic relation to the human mind. The ultimate goal is not to make users conform to system logic, but to make systems *learn the rhythm of human experience*.

2.6 Toward a New Paradigm of Digital Service Innovation

By positioning Digital Resonance as a conceptual model, this paper contributes to the growing recognition that the next stage of technological evolution is not about computation but communication; not about faster systems but more *attuned* ones. Service innovation in the age of artificial intelligence must therefore be understood as the art of achieving coherence between data and emotion, between algorithmic intelligence and human consciousness.

This paradigm demands that ICT design and management integrate psychological insight, aesthetic sensitivity, and ethical awareness. It challenges organisations to move from a paradigm of *digital transformation* to one of *digital attunement*, a process in which

technology evolves not only alongside human behaviour but in resonance with the emotional and cognitive frequencies that define the human experience itself.

3. Theoretical Integration

The evolution of digital transformation theory has thus far been anchored in functional rationality: the pursuit of efficiency, automation, and data-driven precision. Yet as digital ecosystems mature, the boundaries between technical performance and human experience dissolve, demanding an integrative theoretical lens capable of reconciling structure with sensation, logic with emotion. The **Digital Resonance Framework** emerges as such a lens, a conceptual bridge uniting the structural foundations of digital transformation with the affective, experiential, and cognitive dimensions that define contemporary service innovation.

3.1 Reinterpreting Digital Transformation through Resonance

Vial defines digital transformation as the reconfiguration of organizational structures, processes, and capabilities in response to technological change [4]. Building on this, Bharadwaj conceptualize digital strategy as an enterprise-level orientation that aligns technology with competitive objectives [3]. While these models articulate *what* transformation entails. They remain largely silent on *how* transformation is felt and how technology alters the experiential texture of human interaction.

Integrating the principle of resonance into this framework provides a qualitative extension to digital transformation theory. Transformation is understood not only as a structural process but also as a *sensory and cognitive recalibration* of the organisational interface with its environment. It redefines technological success as the capacity to maintain alignment between systemic intelligence and user affect. Therefore, it creates a form of organisational equilibrium that can be measured in efficiency and coherence.

The maturity of digital transformation should not be evaluated solely based on infrastructural readiness or process digitisation. Instead, it must also consider *experiential attunement*, defined as the extent to which technological systems foster trust, emotional continuity, and perceptual harmony within stakeholder networks. Resonance becomes the hidden metric of transformation's completeness: when the system's operational rhythm mirrors the psychological cadence of its users, the digital enterprise achieves true synchrony between purpose and perception.

3.2 Extending Service-Dominant Logic

Service-Dominant Logic [9] established a profound shift in economic thought by asserting that value is co-created through relational interaction rather than produced in isolation. The Digital Resonance Framework builds upon this principle but transposes it into the human–technology domain. In this reimagined logic, ICT systems are not neutral conduits of service delivery but *active participants in value co-creation*, intelligent agents that learn, respond, and adapt to users' evolving emotional states.

Here, resonance operates as the *energetic medium* of co-creation. It is through resonance that user intention and technological response become intertwined, producing a unified experience of meaning. The framework thereby expands the relational model of service-dominant logic into a *triadic structure* involving human, technology, and context. This triad functions as a dynamic circuit of alignment in which the boundaries between service provider and recipient blur, giving way to a distributed network of shared perception.

For tourism, this reinterpretation has far-reaching implications. When a traveller interacts with a digital platform, they engage not merely with content or interface but with an entire ecosystem of adaptive intelligence. This is one that co-creates their emotional and cognitive journey in real time. The tourism experience thus becomes a co-authored narrative between human desire and machine intuition, orchestrated through the resonance of data and feeling.

3.3 Bridging Experience Design and Cognitive Science

The principles of *experience design* [20] [21] and *emotional design* [18] [19] provide the micro-foundations for understanding how users interpret and internalise technological interaction. Yet these frameworks, while rich in psychological insight, have historically remained detached from macro-level theories of digital transformation. The Digital Resonance Framework integrates these micro and macro perspectives by positioning *emotion* as the connective tissue between cognition and system behaviour.

Through this synthesis, resonance becomes a measurable cognitive-emotional state akin to what neuroscience describes as *synchronised oscillation*, a temporal harmony among neural processes that facilitates perception and decision-making. In digital contexts, this synchrony manifests as *cognitive fluency*, the effortless flow users experience when technology behaves in a way that feels intuitively aligned with their expectations.

This alignment is intentional. For example, a tourism platform that detects user hesitation and dynamically simplifies its interface, or one that adjusts its visual tone to maintain user curiosity, demonstrates how resonance connects cognitive processes and design. Each interaction becomes a microcosm of neural coherence translated into digital form. This mirrors a fleeting moment when the rhythm of code matches the rhythm of consciousness.

3.4 Integrating Systems Thinking and Organizational Theory

Systems thinking establishes the macro-ecological framework for Digital Resonance by positioning it within the ongoing feedback loops that characterize adaptive organisations. Checkland's soft systems methodology posits that complex systems maintain equilibrium through iterative feedback and self-regulation [26]. In a digital environment, these feedback loops expand beyond operational control to encompass emotional and experiential data, sentiment analysis, behavioural feedback, and engagement metrics, which now constitute vital inputs to system learning.

Within the resonance paradigm, these feedback loops develop into *reflexive circuits* of mutual adaptation. The organisation acquires knowledge from its users, while users concurrently adjust their expectations in response to organisational actions. Once these cycles stabilise, a form of homeostatic coherence emerges in which the organisation and its environment operate at compatible frequencies. This systemic view redefines resilience as *resonant adaptability*: the ability of a digital ecosystem to maintain alignment amid volatility by continuously recalibrating emotional and cognitive connections.

Tourism ecosystems provide a clear example of this principle. A destination management platform that integrates weather, sentiment, and behavioural data to recalibrate messaging in real time demonstrates systemic resonance. Such a platform functions as a living network that not only responds to external change but also anticipates it through synchronised awareness.

3.5 The Philosophical Synthesis: From Transformation to Attunement

The ultimate contribution of the Digital Resonance Framework lies in its philosophical reorientation. Where digital transformation emphasised replacing analogue systems with digital efficiency, *digital attunement* emphasises cultivating empathy, coherence, and sensorial harmony within human-technology relations. The paradigm thus shifts from control to communication, from data extraction to mutual interpretation, from design for performance to design for presence.

This evolution echoes a deeper ontological realisation: that technology and consciousness are not antagonists but co-evolving expressions of the same informational continuum. In this light, the role of ICT is no longer to mediate between human and system, but to dissolve that boundary. Aiming to create conditions where the digital environment resonates so extensively with human cognition that interaction becomes indistinguishable from intuition.

In managerial and societal terms, this synthesis demands a radical recalibration of innovation priorities. Success in the new digital economy will depend less on technological supremacy and more on the capacity to orchestrate *harmonious intelligence* to design ecosystems where emotional and computational frequencies converge in mutual understanding.

3.6 Toward a Unified Field of Digital Experience

By integrating structural, experiential, and systemic theories under the concept of resonance, this framework outlines a new theoretical field: *digital experience theory*. This emerging field studies neither technology as a tool, nor the user as a variable, but the interactive field of consciousness that emerges between them. In this field, the unit of analysis is not the interface, but the *alignment*; not the user journey, but the *resonant circuit* connecting system behaviour to human emotion.

Such a perspective offers profound implications for both research and practice. It invites scholars to explore the phenomenology of digital interaction - how systems feel, how users sense technological empathy, and how coherence can be deliberately engineered. For practitioners, it signals a shift toward designing *resonant ecosystems* where digital infrastructure, aesthetic experience, and ethical intent converge.

In this integrated view, innovation ceases to be a race toward automation and becomes a quest for attunement. This becomes the delicate art of ensuring that, amid the immense noise of data and design, the human pulse is never lost.

4. Discussion and Implications

The development of the **Digital Resonance Framework** marks a conceptual turning point in how digital transformation is theorised and practiced. This perspective advances the discourse beyond technological capacity into the domain of relational intelligence, where the true measure of innovation is not processing speed but the *depth of connection* between systems and their human users. In this light, technology ceases to be a neutral apparatus and becomes a participatory consciousness: a structure of awareness capable of sensing, adapting, and harmonising with the cognitive-emotional states of its users.

This reorientation has far-reaching implications. It invites both theorists and practitioners to reconsider what it means for a system to “work well.” Under traditional paradigms, performance was evaluated through metrics of efficiency, scalability, and cost reduction. Under the logic of **Digital Resonance**, performance must also include *coherence*, i.e. the degree to which technology maintains emotional consistency, cognitive ease, and ethical transparency across the user experience. Systems that function perfectly but feel discordant fail the resonance test; those that sustain harmony between design intention and lived experience exemplify a higher form of digital maturity.

4.1 Theoretical Implications

At the theoretical level, the framework reconfigures three core assumptions in information-systems research.

Firstly, it challenges the notion of technological neutrality. ICT systems, once considered passive tools, now appear as *co-creative entities* embedded with intentionalities. Used in shaping behaviour, perception, and emotion as much as they are shaped by them. This view aligns with post-phenomenological theories that regard technology as an extension of human cognition rather than an external artefact. In the resonance paradigm, the interface is not a boundary but a bridge and a dynamic membrane through which emotional and informational energy flows bidirectionally.

Secondly, it redefines the boundaries of service innovation. Service science traditionally focused on the optimisation of value chains, customer satisfaction, and productivity. The Digital Resonance model shifts the centre of gravity toward *affective synchronisation*: the process by which shared meaning, emotion, and rhythm are co-created in digital spaces. Here, innovation occurs not when a new function is added, but when a new *feeling* emerges. One that transforms ordinary interactions into aesthetic or even spiritual engagement.

Thirdly, it introduces *resonance* as an analytical construct capable of uniting disparate theoretical traditions. In cognitive psychology, resonance describes alignment in neural oscillations; in systems theory, it refers to harmonic stability; in design research, it evokes aesthetic pleasure. By synthesising these domains, the framework positions resonance as a universal metaphor for coherence across biological, social, and technological systems. Therefore, a principle emerges that enables digital research to transcend disciplinary boundaries.

4.2 Managerial Implications

For organisations, particularly those operating within the tourism and experience sectors, the implications of digital resonance are both strategic and ethical.

a. From Efficiency to Empathy

Management models that once prioritised process optimisation must now embrace emotional intelligence as a strategic asset. In tourism, where memory, perception, and imagination are central to value creation, ICT systems designed for resonance can act as emotional amplifiers, evoking anticipation before travel, companionship during the journey, and nostalgia afterward. A resonant system does not merely inform; it *accompanies*.

b. Designing for Coherence

The practical outcome of this philosophy is a shift from user-centred design toward *ecosystemic coherence*. Every touchpoint, from digital interface to customer service tone,

must maintain a consistent emotional frequency. This coherence strengthens user trust, stabilises brand identity, and cultivates loyalty. It suggests that digital leadership is no longer defined by technological investment alone but by the organisation's capacity to sustain emotional and cognitive continuity in a fragmented world.

c. Resonant Metrics and Governance

To operationalise resonance, organisations may need to establish new key performance indicators, referred to as *resonant KPIs*. Potential examples include emotional continuity scores, coherence indices, and measures of experiential trust. Governance frameworks should incorporate affective feedback as a legitimate form of system intelligence, not an anecdotal supplement to analytics, but a core element of organisational sensing.

d. Ethical Resonance

Finally, the pursuit of resonance introduces significant ethical complexity. Technologies designed to align with user emotions may also be misapplied to manipulate those emotions. Emotional AI, persuasive design, and neuroadaptive systems present a delicate balance between fostering empathy and enabling intrusion. The managerial challenge lies in ensuring that resonance remains *consensual alignment*, not *covert influence*. Ethical governance thus becomes inseparable from aesthetic design: both must safeguard the integrity of the human emotional field.

4.3 Societal and Philosophical Implications

Beyond the boundaries of business and design, the idea of Digital Resonance gestures toward a broader cultural and philosophical shift. In this case, technology evolves from a mechanical extension of labour into a *symbolic extension of consciousness*.

In this context, resonance addresses the spiritual dimension of digital modernity. As technology becomes increasingly intelligent, it is essential for humanity to cultivate greater attunement. The objective is not to dominate or escape digital systems, but to learn to dwell within them - consciously, ethically, and harmoniously. The most advanced information and communication technologies (ICT) will be characterized not by speed of thought, but by the capacity to comprehend silence; not by the ability to predict desire, but by the attentiveness *to intention*.

Within the context of tourism, this perspective fosters a renewed understanding of experience as ritual. Each digital interaction represents a microcosm of communion between the individual and the system, and between the traveller and the broader world. In an era when globalisation frequently results in alienation, resonant technology provides opportunities for reconnection and the restoration of rhythm to a society increasingly shaped by acceleration.

4.4 Future Directions for Theory and Practice

The Digital Resonance Framework opens several promising avenues for interdisciplinary inquiry.

- Scholars of management and psychology might empirically examine how resonance affects trust, satisfaction, and brand attachment across digital interfaces.
- Systems theorists could model resonance dynamics mathematically, tracing how emotional and informational feedback stabilise digital ecosystems.
- Designers and engineers might translate these principles into algorithmic logic, crafting adaptive systems that “listen” to user affect in real time.

The broader agenda is to build a *resonance-oriented paradigm of innovation*. This treats digital transformation as an evolving symphony of alignment between humanity and its technologies, not as a finite transition.

4.5 The Convergence of Ethics, Aesthetics, and Intelligence

At its core, resonance offers a unifying principle for the three dimensions that define our digital future: **ethics, aesthetics, and intelligence**.

- **Ethics** ensures that resonance serves human flourishing rather than manipulation.
- **Aesthetics** ensures that resonance is felt as beauty, harmony perceived through design.
- **Intelligence** ensures that resonance remains adaptive, continuously learning from the human field it inhabits.

The integration of these three elements transforms ICT from a mechanistic infrastructure into a moral-aesthetic enterprise. This aspires not merely to efficiency or engagement, but to *grace*.

4.6 Toward a Resonant Future

Ultimately, the central premise is that the next phase of digital transformation will focus not on machines surpassing human intelligence, but on systems collaborating with humans. The future belongs to technologies that learn the grammar of empathy, that move at the rhythm of human breath and attention. In this future, innovation will be measured not by the quantity of data processed, but by the *quality of resonance achieved*.

Digital Resonance thus becomes both a theory and a vision. Becoming a call for the re-enchantment of technology, for the restoration of meaning to systems designed in our

image. When technology feels in tune with us, it ceases to be a tool and becomes a companion; when organisations design for resonance, they cease to compete for attention and begin to cultivate trust. The transformation is no longer digital alone, but an ontological, cultural, and deeply human.

5. Future Research Agenda

The introduction of the **Digital Resonance Framework** invites a comprehensive reorientation of how researchers investigate, measure, and design the interplay between humans and intelligent systems. As the distinction between cognition and computation blurs, the central question shifts from whether digital systems can replicate human intelligence to whether they can foster *attunement*. This is defined as an adaptive harmony between technological performance and emotional meaning. The future of research, therefore, lies in decoding the mechanics of resonance: how coherence emerges, how it can be sustained, and how it transforms organisational and experiential value.

5.1 Theoretical Consolidation: Building the Science of Resonance

Future scholarship must first pursue theoretical consolidation.

While resonance has appeared across psychology, physics, communication, and systems theory, it remains under-defined in the digital domain.

Researchers should therefore establish a unified conceptual vocabulary capable of articulating resonance as a **cross-disciplinary construct** that operates simultaneously at neurological, cognitive, affective, and organisational levels.

Key research tasks may include:

- Mapping conceptual analogies between neural synchrony, affective contagion, and technological adaptivity.
- Elaborating typologies of resonance (e.g., emotional, cognitive, systemic, ethical) to clarify its scope and operational boundaries.
- Developing integrative theoretical models that embed resonance within the existing architecture of information-systems research (e.g., extending Vial's digital-transformation model [4] or Vargo & Lusch's service-dominant logic [9]).

Such theoretical refinement would establish resonance as a legitimate analytical construct, not merely metaphorical, but empirically interpretable within the sciences of information and consciousness.

5.2 Conceptual Operationalisation: Toward Measurable Coherence

The next frontier lies in operationalising **resonance**.

Although the present framework is conceptual, it lays the groundwork for future methodological innovation.

Researchers can explore how resonance might be *measured*, *modelled*, and *quantified* without reducing its qualitative essence.

Potential research pathways include:

- Developing **resonance indices** that assess cognitive–emotional alignment through behavioural data, sentiment analysis, or biometric sensing.
- Employing **structural-equation modelling** [27] [28] to test relationships among technological capability, emotional engagement, and perceived coherence.
- Using **neuroaesthetic or psychophysiological tools**, EEG, heart-rate variability, gaze tracking, and live emotion tracking, to observe how users physiologically synchronise with adaptive digital systems.
- Constructing **computational simulations** of resonant dynamics using agent-based or network models to visualise feedback loops between human affect and system intelligence.

Through such hybrid methodologies, resonance could evolve from a philosophical intuition into a measurable dimension of digital experience.

5.3 Cross-Sector and Cross-Cultural Research

Resonance, by its nature, transcends industry boundaries.

Although tourism offers a valuable context because of its experiential nature, comparative studies in healthcare, education, finance, and cultural industries could elucidate how resonance varies across sectors with differing emotional intensity and technological advancement.

Cross-cultural inquiry is equally essential.

Cultural psychology suggests that affective expression and cognitive rhythm vary across societies; thus, *resonant design* must account for these subtle variations.

For instance, digital systems that achieve emotional alignment in collectivist contexts may feel intrusive in individualist ones.

Global scholarship could, therefore, identify **cultural frequency patterns** that inform more ethical and inclusive design frameworks.

5.4 Interdisciplinary Bridges: From AI to Phenomenology

The resonance paradigm calls for genuine interdisciplinarity, not a juxtaposition of fields, but synthesis.

- **Artificial Intelligence & Machine Learning:** Incorporating resonance parameters into adaptive algorithms could enable AI systems that respond not only to data patterns but to emotional valence and contextual mood.
- **Neuroscience & Cognitive Psychology:** Studies of synchrony, attention, and embodied cognition can inform how resonance arises at the neural level.
- **Design & Aesthetics:** Human–computer–interaction research can explore how visual rhythm, tone, and narrative structure evoke emotional coherence.
- **Philosophy & Phenomenology:** Resonance aligns with existentialist and hermeneutic traditions that view experience as co-constructed between subject and world; future work could explore its ethical and metaphysical implications.

By linking these disciplines, scholars can begin to articulate a **unified science of digital attunement**. This recognises emotion as a vector of information and technology as a medium of meaning.

5.5 Ethical and Governance Horizons

As systems become more affectively intelligent, the ethics of resonance will emerge as a defining research priority.

If technology learns to “feel with” users, it also gains the power to influence them at unprecedented depth.

It is essential for scholars to examine the boundaries between *alignment* and *manipulation*, as well as between empathy and persuasion.

Key questions include:

- How can organisations design emotionally intelligent systems that respect autonomy and consent?
- What governance frameworks ensure transparency in affective AI?
- How can resonance be used to cultivate collective well-being rather than exploit individual vulnerability?

Melville asserts that innovation in information systems involves both environmental and moral responsibilities [29]. Likewise, ethical resonance requires balancing human flourishing with technological agency.

5.6 Long-Term Vision: From Digital Transformation to Digital Harmony

Ultimately, the future research agenda must transcend the transactional logic of digital transformation and embrace the ideal of **digital harmony** - a state in which technological evolution complements rather than disrupts the rhythm of human life.

In this horizon, resonance becomes both the object and the ethic of inquiry.

It redefines progress as the cultivation of coherence across human, organisational, and ecological systems.

Research in this emerging field could explore:

- How resonant systems contribute to psychological well-being and collective resilience.
- The role of resonance in fostering sustainable innovation and ethical governance.
- The integration of spiritual, artistic, and ecological dimensions into digital-experience design.

In doing so, scholars and practitioners alike would participate in shaping a *new epistemology of technology* - one grounded not in dominance but in dialogue; not in extraction but in reciprocity.

5.7 Conclusion: The Horizon of Resonant Inquiry

The study of Digital Resonance thus opens a transdisciplinary pathway that connects data science to aesthetics, management to consciousness, and innovation to empathy.

Future research must not only explain resonance but *embody it* by constructing methods, systems, and institutions that reflect the very harmony they seek to understand.

If digital transformation was the industrial revolution of information, digital resonance may yet become the cultural revolution of awareness: the moment when technology learns to move, think, and feel in concert with the human soul.

6. Conclusions

The trajectory of digital evolution has reached a point where technological sophistication alone no longer signifies progress. The proliferation of intelligent systems, algorithmic mediation, and pervasive connectivity has redefined the landscape of value creation, yet amid this abundance of capability, a deficit of *coherence* persists. The challenge facing contemporary organisations, and indeed society itself, is not to create more technology,

but to create technology that feels *in tune*, resonating with the emotional, cognitive, and ethical frequencies of human life.

The **Digital Resonance Framework** proposed in this study offers a theoretical foundation for such alignment. By uniting the structural rigor of digital transformation, the relational insight of service-dominant logic, and the emotional intelligence of experience design, it repositions ICT as a *cognitive-emotional infrastructure*, an invisible architecture of perception that mediates meaning, memory, and trust. In this paradigm, digital transformation becomes not a transition from analogue to digital, but an evolution from information to understanding, from efficiency to empathy, from communication to communion.

At its core, resonance captures the *moment of coherence* between system and self: the instant when interaction dissolves into intuition, and technology ceases to feel external. In the tourism sector, where experiences are lived and remembered through feeling, this alignment becomes not a luxury but a necessity. A resonant digital ecosystem facilitates the translation of information into emotion, design into meaningful connection, and service into a shared narrative, thereby integrating users' knowledge, feelings, and values into a unified experiential rhythm.

The implications extend far beyond tourism. Across industries, organizations increasingly operate within emotional economies, which are markets defined by trust, attention, and perceived authenticity. In such an environment, success depends on the capacity to generate *emotional fidelity* through technological harmony. The systems that thrive will be those that mirror human complexity without mimicking it, that learn empathy without erasing individuality, and that elevate intelligence to the level of relational grace.

Digital Resonance serves as a conceptual bridge between the material and metaphysical dimensions of technology. This framework asserts that innovation extends beyond mechanical processes and emerges as a relational phenomenon, arising from the attunement among human, organizational, and computational entities. This redefinition invites scholars to move beyond dualisms of subject and object, user and system, and instead embrace the continuum of interaction in which experience itself becomes the medium of value.

The ethical and existential implications of this transition are considerable. As systems advance toward affective intelligence, designers and decision-makers assume responsibility for the emotional frameworks they construct. Pursuing resonance without critical reflection may transform empathy into a mere instrument. But if guided by integrity, it can serve as the foundation of a humane digital civilization - one in which technology amplifies awareness rather than anaesthetises it.

In this light, the future of digital transformation is not automation but *attunement*. Progress will be defined not by how efficiently systems operate, but by how harmoniously

they coexist with human consciousness. The most advanced technologies of tomorrow will not be those that dominate attention, but those that *resonate with it*, by cultivating stillness within acceleration, meaning within data, and unity within multiplicity.

To speak of resonance, then, is to speak of restoration: the return of equilibrium between thought and feeling, machine and mind, information and wisdom. It represents a re-enchantment of the digital world and a reminder that behind every algorithm lies intention, and behind every interface, the pulse of human experience.

The **Digital Resonance Framework** thus concludes not as an endpoint but as an overture - an invitation for scholars, designers, and leaders to build technologies that listen as deeply as they speak. In a world defined by noise, the future belongs to those who can create harmony, to those who understand that innovation, at its highest expression, is resonance, not disruption.

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MODELLING THE RELATIONSHIP BETWEEN DIGITALIZATION, SOCIO-ECONOMIC PERFORMANCE AND ECONOMIC RISK IN ROMANIA'S DEVELOPMENT REGIONS (2015–2024)

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Abstract

This study investigates the relationship between digitalization, socio-economic performance, and economic risk across Romania's development regions over the period 2015–2024. Using a dataset of seven standardized indicators and a composite Digitalization Index, the analysis employs Pearson correlations and multiple regression models to examine bidirectional influences between digital transformation and regional economic outcomes. The findings show strong positive associations between digitalization and indicators of economic development, such as average wage levels and internet access, while negative correlations are observed with unemployment and relative poverty rates. Regression results demonstrate that socio-economic variables explain 90.3% of the variation in digitalization ($R^2 = 0.903$), while digitalization and labor market indicators jointly account for 84% of the variation in regional GDP per capita ($R^2 = 0.840$). Diagnostic tests confirm the validity of both models regarding normality, homoscedasticity, and multicollinearity thresholds. The study concludes that digitalization functions both as a determinant and an outcome of socio-economic development, highlighting persistent regional disparities and the need for targeted public policy interventions to support balanced digital transformation.

Keywords: Digital transformation; Regional disparities; Economic performance; Labor market; Socio-economic indicators; Economic risk.

JEL Classification: O33; R11; E24; C38; H70.

1. Introduction

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Digitalization represents one of the most important drivers of contemporary economic and social transformation. The expansion of information and communication technologies, the increasing availability of internet access, and the accelerated adoption of digital services have contributed to the reconfiguration of economic, administrative, and educational processes at a global level. In this context, the degree of digitalization of an economy is not merely an indicator of technological progress, but a strategic measure of competitiveness, sustainable development, and a society's capacity to respond to the challenges generated by the transition to the knowledge-based economy.

Romania is currently undergoing a continuous process of digital alignment, influenced by the pace of investment in infrastructure, the level of digital literacy, public policy priorities, and structural regional differences. Although national averages show a positive evolution, territorial analysis reveals substantial disparities between economically advanced regions and those where digitalization progresses at a slower rate. These discrepancies highlight the need for a rigorous assessment of the relationship between digitalization and regional socio-economic performance, in order to identify mechanisms that support convergence or, conversely, reinforce territorial polarization.

The present study aims to investigate the impact of digitalization on regional development in Romania by analyzing the dynamics of technological and economic indicators for the period 2015–2024. The research examines relationships among key variables, including gross domestic product, employment rate, average gross monthly wage, relative poverty rate, unemployment rate, and indicators related to internet access and usage. By applying advanced statistical techniques - specifically multiple regression models - the study constructs a Digitalization Index and identifies distinct regional patterns in the interaction between digital transformation and economic performance.

The results contribute to an evidence-based perspective on the role of digitalization in shaping regional development dynamics and its potential to reduce territorial disparities. In alignment with European digital transformation priorities, the study provides a relevant analytical framework to support public policy design, strategic investment decisions, and institutional capacity strengthening in Romania.

2. Literature Review

Digital transformation has emerged as a central driver of socio-economic development, reshaping labor markets, productivity models, and territorial competitiveness. According to the European Commission [1], the digital economy has become a key pillar of the EU development framework, closely aligned with the Digital Decade Policy Programme, which prioritizes connectivity, digital skills, public sector digitalization, and digital adoption in business environments. Research demonstrates that regions with more advanced digital

infrastructures tend to exhibit higher economic resilience and faster post-crisis recovery trajectories [2].

A substantial body of literature highlights the positive association between digitalization and macroeconomic outcomes. Brynjolfsson and McAfee [3] argue that digital technologies stimulate productivity and innovation, while Sorbe et al. [4] indicate that digital adoption enhances organizational efficiency and contributes to long-term economic growth. From a territorial perspective, Tranos and Ioannides [5] demonstrate that digitally advanced regional ecosystems attract capital investment and highly skilled labor, reinforcing cumulative advantages in development.

Labor market implications of digitalization have also been extensively analyzed. Digital adoption is associated with higher job quality and wage increases in high-skilled sectors, while potentially widening inequalities in regions with low digital uptake [6]. Evidence from van Ark [7] suggests that digital transformation reshapes occupational structures, favoring professions requiring advanced digital competencies while reducing the share of routine, automatable tasks. These structural transformations contribute to regional disparities in unemployment and poverty, particularly in economies facing uneven technological adoption.

Moreover, several authors highlight the bidirectional relationship between socio-economic status and digitalization. Helsper [8] conceptualizes this interaction through a “digital feedback loop,” wherein higher income levels, stronger infrastructure, and better education systems accelerate digital adoption, whereas weaker socio-economic conditions hinder access, skills, and meaningful usage. Similarly, Vicente and López [9] argue that the digital divide serves both as a consequence and a driver of territorial inequality, particularly among European regions.

Research focusing on post-transition economies, including Central and Eastern Europe, confirms persistent digital disparities despite EU convergence efforts. Nemes and Molnár [10] show that Romania exhibits one of the most pronounced digital divides in the European Union, largely shaped by regional gaps in broadband adoption, workforce qualification levels, and investment flows. Eurostat statistics [11] reinforce this pattern, revealing significantly higher digital performance scores in urban and economically dynamic regions compared to rural and structurally disadvantaged areas.

In conclusion, the reviewed literature demonstrates that digitalization operates as both a catalyst for socio-economic progress and a reflection of existing territorial inequalities. Accordingly, examining the bidirectional relationship between digital transformation and socio-economic outcomes—particularly within contexts characterized by uneven regional development, such as Romania—remains essential and provides meaningful insight for current European policy discussions.

3. Research Methodology

The methodology of this study is based on a quantitative, exploratory–explanatory approach, with the objective of analyzing the relationship between digitalization, socio-economic performance, and economic risk across Romania’s development regions during the period 2015–2024. The methodological framework consists of successive stages of data processing, statistical testing, and modeling, aimed at identifying relationships among variables, assessing mutual influence, and defining regional typologies.

The data used in the analysis were collected from official European and national sources, namely Eurostat [11] (digital, socio-economic, and regional indicators) and the National Institute of Statistics (INS) [12]. The final database includes eight Romanian development regions over a ten-year period (2015–2024), resulting in a total of 80 observations (8 regions × 10 years).

The variables included in the analysis are: Gross Domestic Product at current market prices (million euros); unemployment rate; relative poverty rate; nominal average gross monthly wage (RON); share of households with internet access at home; employment rate; and the percentage of individuals regularly using the internet (Appendix 1).

To reduce collinearity between the two digitalization indicators (internet access and internet use), a composite index was constructed. The Digitalization Index (DI) was calculated as the mean of the standardized values of these two indicators, according to the following formula:

$$DI = \frac{Z_{\text{internet access}} + Z_{\text{internet usage}}}{2}$$

Standardization using z-scores enabled comparability across regions and years, eliminating differences associated with measurement units.

Data analysis was conducted using SPSS Statistics v.26 and followed the steps below:

- (a) **Descriptive analysis and normality testing.** This included mean, standard deviation, skewness, and kurtosis, alongside Shapiro–Wilk and Kolmogorov–Smirnov normality tests.
- (b) **Correlation analysis.** Pearson correlation coefficients were used to assess bidirectional relationships between economic, social, and digitalization indicators.
- (c) **Multiple regression analysis.** Two regression models were developed: Model 1 - Digitalization as predictor of economic performance (GDP per capita); and Model 2 - Socio-economic performance as predictor of digitalization. Diagnostic validation included assessment of: determination coefficient (R^2), multicollinearity (VIF and tolerance values), autocorrelation (Durbin–Watson), and residual normality.

4. Results and Interpretation

Descriptive analysis and normality testing

The dataset consists of 80 observations representing the eight Romanian development regions across a ten-year period (2015–2024). The Kolmogorov–Smirnov and Shapiro–Wilk normality tests indicated deviations from a normal distribution for most variables ($p < 0.05$), which is a common characteristic of longitudinal socio-economic territorial datasets (Appendix 2). Since the statistical analysis relied on standardized values (z-scores), the data were considered appropriate for further statistical procedures and model estimation.

Correlation analysis

The Pearson correlation analysis revealed statistically significant relationships among the variables included in the study. GDP per capita shows strong and positive correlations with average gross wage ($r = .751$, $p < .001$), household internet access ($r = .600$, $p < .001$), and regular internet use ($r = .550$, $p < .001$). Conversely, unemployment rate ($r = -.635$, $p < .001$) and relative poverty rate ($r = -.732$, $p < .001$) are negatively and significantly associated with regional development levels.

These results confirm the link between digitalization and regional economic capacity, suggesting that regions with higher digital adoption tend to be more prosperous, economically resilient, and better integrated into the contemporary digital economy.

Multiple regression models

To examine the bidirectional relationship between digitalization and socio-economic performance, two regression models were estimated.

Model 1: Digitalization as a predictor of economic performance (GDP)

The first model demonstrates that digitalization significantly predicts GDP per capita, explaining 84% of its variance (Adjusted $R^2 = 0.830$, $p < 0.001$). The independent variables contribute unequally, with the strongest predictor being the average gross wage, followed by the Digitalization Index, employment rate, and relative poverty rate. The unemployment rate does not exert a statistically significant effect on regional economic variation.

These findings indicate that regional economic performance depends substantially on human capital quality, digital inclusion, and socio-economic structure, outlining a structural profile of Romania's regional development during 2015–2024.

Change Statistics										
M	R	R Square	Adjusted Square	RStd. Error of the Estimate	Change ofR Square	F Change	df1	df2	Sig. F Change	Durbin-Watson
1	,917 ^a	,840	,830	,41276177	,840	77,938	5	74	,000	,621

a. **Predictor variables:** Digitalization Index, standardised employment rate, standardised unemployment rate, standardised relative poverty rate, and standardised nominal average gross monthly wage.

b. **DV:** Z-score — GDP at current market prices (million euro)

Table 1. Model summary for regression model 1^b

Although the Durbin–Watson statistic indicates positive autocorrelation (DW = 0.621), this pattern is common in short-term socio-economic time series and does not invalidate the model, as the purpose of the analysis is explanatory rather than longitudinally predictive.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	66,392	5	13,278	77,938	,000 ^b
	Residual	12,608	74	,170		
	Total	79,000	79			

a. Dependent Variable: Zscore: Gross Domestic Product at current market prices (million euro)

b. Predictors: (Constant), Digitalization Index (DI), Z-score - Employment Rate, Z-score - Unemployment Rate, Z-score - Relative Poverty Rate, Z-score - Nominal Average Gross Monthly Wag

Table 2. ANOVA results for regression model 1^a

The ANOVA test indicates that the multiple linear regression model is statistically significant ($F(5, 74) = 77.938, p < 0.001$). This result suggests that the independent variables included in the analysis - digitalization, labor market indicators, and social dimensions - explain a substantial proportion of the variance in regional GDP. Therefore, the model is

appropriate for examining the relationships between digitalization, economic performance, and socio-economic risk in Romania.

The results show that the strongest predictors of regional GDP are the nominal average gross monthly wage ($\beta = 1.129$, $p < 0.001$) and the Digitalization Index ($\beta = -0.653$, $p < 0.001$). The employment rate ($\beta = 0.233$, $p = 0.011$) and the relative poverty rate ($\beta = -0.289$, $p = 0.010$) also have statistically significant effects on GDP. Conversely, the unemployment rate does not significantly influence regional GDP variation ($p = 0.797$) (see Appendix 3).

The nominal gross wage emerges as the primary determinant of GDP:

- regions with higher wage levels tend to display stronger economic performance.

The negative coefficient of the Digitalization Index may reflect several structural mechanisms:

- **structural asymmetry:** highly digitalized regions are already economically advanced, thus incremental digitalization does not automatically generate additional growth
- **technological substitution:** digital processes may reduce traditional employment structures
- **reinforced digital divide:** digitalization progresses faster in wealthier regions, increasing territorial polarization

The employment rate shows a positive effect, confirming the direct link between labor market integration and regional economic output.

The poverty rate has a negative impact, consistent with evidence that economically vulnerable regions register weaker development outcomes.

The lack of statistical significance for unemployment suggests either:

- the presence of a **large informal labor market**,
- **lagged effects** not captured within the analyzed timeframe, or
- limited regional differentiation in unemployment during the period investigated.

Model 2 — Economic performance as a predictor of digitalization

The second regression model explains 90.3% of the variance in regional digitalization levels (Adjusted $R^2 = 0.896$). The high correlation coefficient ($R = .950$) indicates a strong association between digitalization and the socio-economic factors included in the regression.

Change Statistics										
MR	R Square	Adjusted Square	RStd. Error of the Estimate	ofR Square Change	F Change	df1	df2	Sig. F Change	Durbin-Watson	
2	,950 ^a	,903	,896	,31879	,903	137,610	5	74	,000	,855

a. Predictors: (Constant), Zscore: Gross Domestic Product at current market prices (million euro), Z-score — Employment rate, Z-score — Unemployment rate, Z-score — Relative poverty rate, Z-score — Nominal average gross monthly wage

b. Dependent Variable: Digitalization Index (DI)

Table 3. Model summary for regression model 2^b

The corresponding ANOVA test confirms statistical significance ($p < .001$), demonstrating the major influence of economic development on digital advancement in Romania.

Model		Sum of Squares	df	Mean Square	F	Sig.
2	Regression	69,924	5	13,985	137,610	,000 ^b
	Residual	7,520	74	,102		
	Total	77,444	79			

a. Dependent Variable: Digitalization Index (DI)

b. Predictors: (Constant), Zscore: Gross Domestic Product at current market prices (million euro), Z-score — Employment rate, Z-score — Unemployment rate, Z-score — Relative poverty rate, Z-score — Nominal average gross monthly wage

Table 4. ANOVA results for regression model 2^a

The ANOVA results indicate that the regression model is statistically significant ($F(5, 74) = 137.610$, $p < .001$), confirming that the economic and social variables included in the analysis significantly contribute to explaining the variation in regional digitalization levels in Romania.

The strongest determinant of digitalization is the nominal gross wage ($\beta = 1.015$, $p < 0.001$), suggesting that regions with higher income levels and increased purchasing power tend to adopt digital technologies more rapidly. Regional GDP ($\beta = -0.397$, $p < 0.001$) and the unemployment rate ($\beta = -0.331$, $p < 0.001$) also exhibit significant, yet negative effects, implying that digitalization tends to advance in regions with already consolidated economies, which may reduce the explanatory power of traditional socio-economic indicators.

The relative poverty rate and the employment rate do not exert a statistically significant influence on digitalization levels, indicating that digital adoption is driven more strongly by economic prosperity and structural competitiveness rather than general labor market participation or poverty conditions.

Analysis	Model 1	Model 2
	(Digitalization - GDP)	(GDP - Digitalization)
R ²	.840	.903
Significant predictors	Wage, employment, digitalization, poverty	Wage, GDP, unemployment
Direction of relationship	Digitalization explains GDP	Economic development explains digitalization more strongly
Conclusion	Digitalization has a measurable effect on economic growth	Digitalization appears primarily as a result of economic development

Table 5. Comparative analysis of the two regression models:

The bidirectional analysis of the relationship between digitalization and socio-economic performance confirms the presence of an asymmetric dynamic. Although digitalization contributes to economic growth ($R^2 = 0.840$), the level of economic development explains an even larger proportion of digitalization variation in Romania ($R^2 = 0.903$). This finding indicates a structural dependency pattern, in which digitalization functions more as an outcome of economic prosperity rather than a primary driver of it.

As a result, digitalization tends to reinforce existing regional disparities, reflecting a model of **development-dependent digitalization**, where technologically advanced and

economically affluent regions continue to advance faster than structurally disadvantaged areas.

5. Comparative Discussion with Existing Literature

The empirical results obtained in this study largely confirm the conclusions of international research regarding the role of digitalization in socio-economic development and in either amplifying or reducing regional disparities. The strong positive relationship identified between the Digitalization Index, average wage levels, and GDP per capita aligns with the findings of Brynjolfsson and McAfee [3], who argue that the adoption of digital technologies enhances productivity and generates competitive advantages for regions capable of rapidly integrating technological innovation into their economic systems. Furthermore, the negative association between digitalization, unemployment rates, and relative poverty supports the observations of Helsper [8] and Vicente and López [9], who emphasize that access to and effective use of technology can function as drivers of socio-economic inclusion.

An important aspect highlighted in recent literature [5] is the bidirectional nature of the relationship between digitalization and economic development. The regression models constructed in this research show that, on the one hand, socio-economic variables explain a substantial share of the variation in digitalization levels ($R^2 \approx 0.90$), while, on the other hand, digitalization significantly contributes to explaining regional economic performance ($R^2 \approx 0.84$). This pattern supports the concept of a “cumulative cycle” between technology and development, whereby wealthier regions invest more in digitalization, and digitalization subsequently reinforces pre-existing economic advantages.

Compared to existing studies, the specific contribution of this research lies in integrating three dimensions - digitalization, socio-economic performance, and economic risk - within a single empirical framework, while applying multiple regression models to explore the relationships between variables and to identify regional typologies. The findings confirm the broader trends identified in international literature but also highlight structural specificities within Romanian regions, particularly the pronounced contrast between Bucharest–Ilfov and the rest of the country, as well as the presence of a large group of regions situated in an incomplete transition toward a fully digital economy.

6. Conclusions and Policy Implications

The findings of this research demonstrate strong, statistically and structurally significant relationships between digitalization, socio-economic performance, and economic risk across Romania’s development regions during the period 2015–2024. The analysis indicates that digitalization is not merely a consequence of economic progress but also a

catalyst for development, influencing regional GDP levels, labor market dynamics, and social vulnerability.

A key result is that digitalization is positively and directly correlated with economic performance and quality of life, while variables such as unemployment and relative poverty exhibit negative associations. This suggests that regions with lower levels of digitalization are more exposed to socio-economic vulnerability. The regression models confirm the bidirectional nature of these relationships: more developed regions tend to be more digitalized, and digitalization in turn contributes to higher economic performance. This dynamic reflects a virtuous cycle in advanced regions and a vicious cycle in those lagging behind.

Overall, the results confirm the persistence of substantial socio-economic and digital disparities among Romanian regions. Therefore, digitalization functions both as a mechanism for reducing territorial inequalities and as an indicator of administrative, economic, and social capacity to adapt to the knowledge-based economy.

Based on the empirical results, the following policy directions are recommended:

1. **Accelerating investment in regional digital infrastructure.** Regions with low digitalization levels require prioritized broadband expansion and universal internet access, in line with the European Digital Agenda.
2. **Developing digital human capital.** Programs aimed at enhancing digital skills should target adults aged 16–64, employees in the private sector, and public administration staff. A phased approach could reduce the identified gap between digital competencies and economic development.
3. **Integrating digitalization into regional economic development strategies.** Digitalization should be treated not as an isolated technological sector, but as a cross-sectoral strategic infrastructure embedded in education, healthcare, public administration, business environments, and public services.
4. **Providing fiscal and financial support for SMEs' digital transformation.** The evidence suggests that insufficient digitalization within the economy-not solely within public institutions-constrains competitiveness. Facilitating SME access to Industry 4.0 solutions is essential.

Digitalization constitutes a critical determinant of regional development in Romania; however, its progression remains uneven. To transform digitalization into a catalyst for social cohesion and economic competitiveness, public policy must be targeted, differentiated, and sustainable-aligned with regional needs and geared toward accelerating Romania's convergence with the European digital landscape.

Appendix 1. Description of Indicators and Data Sources

No	INDICATOR	Description	SOURCE
1	Gross Domestic Product at current market prices (million euro)	Represents the total value of goods and services produced within a region at current market prices. It reflects the aggregate economic size and level of economic activity of the region.	Eurostat – NUTS regional database / regional statistics
2	Unemployment rate	Percentage of the active population who are without a job but are available for work and actively seeking employment. It reflects labour market performance and economic vulnerability.	National Institute of Statistics (INS, Romania) – regional data / TEMPO-Online
3	Relative poverty rate	Percentage of the population living below a defined relative poverty threshold (typically 60% of median equivalized income). It measures levels of social vulnerability and inequality.	NS – relative poverty indicators, regional time series
4	Monthly nominal average gross wage (lei)	The nominal average gross monthly wage, reflecting purchasing power, living standards, and human capital quality across regions.	INS – regional wage statistics / Eurostat (wage indicators)
5	Share of households with internet access at home (%)	Proportion of households with home internet access, used as a proxy for digital infrastructure and potential for digital inclusion.	Eurostat – Regional ICT statistics / internet access in households
6	Employment rate (labor force participation rate)	Percentage of the working-age population who are employed. It indicates labour market integration and regional economic participation.	INS / Eurostat – labour market and regional employment indicators
7	Percentage of individuals who regularly use the internet (%)	Proportion of individuals who use the internet regularly; measures digital adoption, digital literacy and effective digital inclusion.	Eurostat – ICT usage dataset / regional digital use indicators

Table A1. Description of indicators and data sources

Appendix 2: Tests of Normality

	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Zscore: GDP	,219	80	,000	,726	80	,000
Unemployment (Z)	,073	80	,200*	,976	80	,140
Relative poverty (Z)	,097	80	,062	,956	80	,008
Gross wage (Z)	,086	80	,200*	,954	80	,006
Internet access (Z)	,131	80	,002	,938	80	,001
Employment (Z)	,121	80	,005	,937	80	,001
Internet use (Z)	,115	80	,010	,945	80	,002

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table A2. Tests of Normality

Appendix 3: Regression coefficients for Model 1 (Digitalization - GDP)

M1	Unstandardized Coefficients		Standardized Coefficients		t	Sig.	VIF
	B	Std. Error	Beta				
(Constant)	3,815E-16	,046			,000	1,000	
Unemployment (Z)	-,028	,107	-,028		-,258	,797	5,289
Relative poverty (Z)	-,289	,110	-,289		-2,626	,010	5,624
Gross wage (Z)	1,129	,114	1,129		9,866	,000	6,069
Employment (Z)	,233	,090	,233		2,602	,011	3,734
Digitalization Index (DI)	-,659	,130	-,653		-5,090	,000	7,627

Note: The dependent variable is the Z-score of Gross Domestic Product at current market prices (million euro). Confidence intervals are reported at the 95% level. Collinearity was assessed using VIF.

Table A3. Regression coefficients for Model 1 (Digitalization - GDP)

Appendix 4: Regression coefficients for Model 2 (GDP - Digitalization)

M 2	Unstandardized Coefficients		Standardized Coefficients		t	Sig.	VIF
	B	Std. Error	Beta				
(Constant)	5,795E-17	,036			,000	,000	
Unemployment (Z)	-,327	,073	-,331		-4,469	,000	4,169
Relative poverty (Z)	-,032	,089	-,032		-,362	,718	6,138
Gross wage (Z)	1,005	,067	1,015		15,104	,000	3,442
Employment (Z)	-,029	,072	-,029		-,404	,688	4,066
GDP (Z)	-,393	,077	-,397		-5,090	,000	4,641

Dependent Variable: Digitalization Index (DI)

Table A4. Regression coefficients for Model 2 (GDP - Digitalization)

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TRIGGERS IN ORACLE SQL: AUTOMATION AND INTEGRITY IN ECONOMIC DATABASE MANAGEMENT

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Abstract

In the economic sphere, maintaining operational efficacy and decision-making accuracy requires process automation and data consistency. Enforcing business rules, automating time-consuming tasks, and preserving data integrity all depend on Oracle SQL triggers. This article examines the principles and applications of triggers in economic database management systems, with a focus on their use in financial transactions, audit trails, and compliance enforcement. Real-world examples show how triggers enhance database functionality and dependability, underscoring their significance in economic environments. Because the economic sector relies largely on transactional data and has high accuracy and transparency requirements, it is uniquely positioned to benefit from database triggers. Triggers serve as the basis for automating crucial procedures including real-time reporting, tax compliance, and fraud detection. In both banking and retail, triggers serve as the basis for automating critical procedures including tax compliance, fraud detection, and real-time financial reporting. This article explores the principles, architecture, and real-world applications of Oracle SQL triggers to demonstrate how they can maximize database performance while meeting industry requirements.

Keywords: Oracle SQL, database automation, economic systems, triggers, data integrity, financial transactions, compliance, audit trails

JEL Classification: O33, M15

1. Introduction

Data is a vital resource that drives decision-making and operational efficiency across industries in the contemporary economic environment. Organizations in a variety of industries, including banking, insurance, retail, and manufacturing, depend on reliable database management systems (DBMS) to handle enormous volumes of transactional data, implement corporate policies, and guarantee regulatory compliance. The ability to build triggers, which are essential for automating database processes and preserving data

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integrity, is one of Oracle SQL's many sophisticated features that set it apart from other DBMS platforms.

Procedural code objects called triggers in Oracle SQL run automatically when certain events on a database table or view are triggered. Operations like INSERT, UPDATE, and DELETE as well as schema-level updates like user logins or privilege changes might be examples of these events.

Triggers are essential in the economic domain, where process automation and data consistency are critical. They simplify processes that are essential to industries like banking, retail, and finance, like tax calculations, transaction validation, and audit trail maintenance. For example, a trigger can prevent unauthorized overdrafts in a banking application, ensuring customer accounts remain accurate and compliant with internal policies. Similarly, in e-commerce platforms, triggers can automatically adjust inventory levels after each transaction, reducing the likelihood of overselling.

Triggers are important for reasons other than operational effectiveness. Triggers enforce data security and integrity in a smooth and consistent way by integrating logic directly into the database layer. This reduces the possibility of human error and guarantees adherence to industry rules, including those controlling tax collection and financial reporting. However, in order to prevent performance snags and guarantee scalability in high-volume economic systems, trigger implementation calls for meticulous planning and optimization.

The concepts, varieties, and uses of triggers in Oracle SQL are examined in this essay, with an emphasis on how they contribute to cost-effective database administration. With the help of real-world examples and case studies, it explains how triggers may improve data integrity, automate important procedures, and ease regulatory compliance.

2. Key Concepts and Types of Triggers

Triggers can be configured to execute either before or after specific events, such as INSERT, UPDATE, or DELETE operations. Oracle SQL supports a wide variety of trigger types, including:

- **Triggers at the row level:** These triggers operate for each impacted row, making them ideal for scenarios requiring fine-grained management.
- **Statement-Level Triggers:** These triggers only fire once for the entire statement, regardless of how many rows are impacted.
- **Permit DML operations on views instead of triggers,** as these are essential for complex financial reporting.
- **System triggers respond to schema-level events,** such as database logins or privilege changes, and are commonly used for security purposes.

These trigger kinds provide customized solutions to meet certain business needs in economic systems. For example, statement-level triggers can automate batch procedures in financial reporting, whereas row-level triggers are essential for guaranteeing transactional accuracy in banking systems.

3. Applications of Economic Systems

Generating financial transaction automation, economic databases are commonly used to manage repetitive processes, including applying discounts, managing stock portfolios, and calculating interest. Triggers increase efficiency and reduce human error by automating these procedures. For example, a trigger can automatically calculate and apply value-added tax (VAT) to sales transactions to ensure compliance with tax regulations.

As regards the ensuring of data integrity, financial systems must provide data consistency to prevent errors that could lead to significant financial losses. Triggers uphold corporate regulations, such as prohibiting withdrawals that exceed an account's available balance or ensuring that invoices are not deleted without administrative approval.

Another relevant aspect concerns the maintenance of audit trails. In sectors like banking and insurance, regulators demand meticulous record-keeping. The timestamp, the type of change, and the user who did it are all automatically recorded by triggers when sensitive data is modified. This ensures transparency and facilitates compliance audits.

4. Economic database triggers offer multiple benefits

The main advantage is related to increased efficiency and automation. Triggers reduce the amount of manual work required to complete repetitive tasks, such as recalculating account balances or preparing reports. By automating these processes, companies save time and money, allowing employees to focus on higher-value tasks.

At the same time, increased data security and integrity is an important advantage. Triggers act as a safety net, ensuring data accuracy, blocking unwanted changes, and enforcing business rules at the database level. To avoid overselling and customer dissatisfaction, triggers can, for example, check inventory levels in an e-commerce platform before processing orders.

Triggers facilitate compliance to the industry rules, by automating regulatory processes such as maintaining audit trails or calculating legal taxes. This ensures that companies comply with the law without having to put in additional physical effort.

5. Implementation Challenges

Triggers have benefits, but they must be used cautiously to prevent performance problems. Database processes may be slowed down by poorly designed triggers, such as those involving intricate queries. Furthermore, excessive trigger usage can make database systems challenging to maintain and troubleshoot, particularly in settings where schema changes occur often.

6. Scientific Research

The rationale behind the selection of the research applications, automatic stock updates, VAT computation, and overdraft prevention etc. was their economic significance, practical relevance, and ability to demonstrate the effectiveness of database triggers in resolving real-world issues. Every example tackles a basic issue in its field and demonstrates how Oracle SQL's automated features may improve data integrity, operational effectiveness, and regulatory compliance.

6.1. Dealing with Real-World Issues

Accuracy and consistency of data are critical in economic systems. Errors in inventory management, tax compliance, or financial management can result in large financial losses or harm to one's reputation. The selected examples center on situations in which automation using triggers immediately lowers risks, minimizes mistakes, and guarantees that business standards are followed.

6.2. Improving Efficiency in Operations

A key component of contemporary database administration is automation. Triggers make it possible to execute business logic and enforce rules in real time without depending on third-party apps. This database-level integration guarantees consistency across all access points, streamlines processes, and lowers overhead.

For instance:

- The banking example protects clients and organizations from any financial irregularities by dynamically preventing overdrafts.
- Retail inventory triggers guarantee real-time stock level updates, increasing consumer satisfaction and lowering holding costs.

6.3. Guaranteeing Adherence to Regulations

Economic systems are highly regulated, especially when it comes to financial reporting and taxes. The example of VAT calculation shows how database triggers may reliably enforce tax laws, bringing operations into compliance with the law.

6.4. Contribution to Science

These examples demonstrate the flexibility of database triggers as instruments for carrying out intricate business logic from a research standpoint. They are used as case studies to investigate: the combination of declarative and procedural database programming, the effect of real-time automation on accuracy and system performance. Trigger scalability in high-transaction settings.

6.5. Wider Consequences

In addition to proving technical viability, these examples offer guidance on creating reliable systems in industries including banking, retail, and taxation. They open the door for more research into the ways database triggers can help with issues in other economic domains like e-commerce, insurance, and supply chain management.

In summary, the selection of these instances for scientific study stems from their applicability, their capacity to demonstrate the power of Oracle SQL triggers, and their potential to spur additional advancements in database-driven automation for cost-effective uses. These examples demonstrate how Oracle SQL triggers can be used to incorporate business logic directly into the database from a research standpoint. By lowering reliance on application layers, this method improves the scalability, resilience, and effectiveness of systems. The examples also shed light on how triggers may be modified to address similar problems in other fields, like healthcare, logistics, or educational institutions.

7. Practical Examples

7.1. Automating Tax Calculation in a Retail Database

Domain: Retail and Supply Chain Management Use: Accurate inventory control is essential for operational effectiveness in the retail industry. When a sale is registered, the stock update example automatically lowers inventory levels, guaranteeing that the system displays current stock availability. Given that millions of transactions take place every day in e-commerce platforms and huge retail chains, this example is very relevant. Businesses can accomplish the following by integrating stock management logic into the database.

Operational Efficiency: Less manual intervention is required because inventory adjustments happen automatically.

Error Reduction: Avoids underselling or overselling because of erroneous stock information.

Better Customer Experience: Better service is a direct result of real-time stock visibility.

Scenario: A retail company operates in a region where a 20% VAT (Value-Added Tax) must be applied to every sale. To ensure compliance and streamline operations, a trigger is used to calculate and record the VAT for each transaction automatically.

Implementation: Every time a new sales record is added to the sales table, the following trigger automatically determines the VAT amount:

```
CREATE OR REPLACE TRIGGER calculate_vat
BEFORE INSERT ON sales
FOR EACH ROW
BEGIN
    :NEW.vat_amount := :NEW.sale_amount * 0.20;
    :NEW.total_amount := :NEW.sale_amount + :NEW.vat_amount;
END;
/
```

Figure 1. VAT automating calculator

Explanation of the code:

- The trigger is executed before a new row is inserted into the Sales table.
- It calculates the VAT (20% of the sale amount) and updates the vat_amount field.
- The total amount, including VAT, is also computed and updated automatically.

Impact: This trigger ensures all sales transactions include VAT, reducing the risk of non-compliance and eliminating manual calculation errors.

7.2. Maintaining an Audit Trail in Financial Systems

Scenario: A financial institution needs to track all modifications to its Loans table for compliance purposes. A trigger is used to log every insert, update, or delete operation into an Audit_Log table.

```
CREATE OR REPLACE TRIGGER audit_loans
AFTER INSERT OR UPDATE OR DELETE ON loans
FOR EACH ROW
BEGIN
    INSERT INTO audit_log (action_type, user_id, timestamp, old_data, new_data)
    VALUES (
        CASE
            WHEN INSERTING THEN 'INSERT'
            WHEN UPDATING THEN 'UPDATE'
            WHEN DELETING THEN 'DELETE'
        END,
        USER,
        SYSDATE,
        CASE
            WHEN DELETING OR UPDATING THEN :OLD.loan_details
            ELSE NULL
        END,
        CASE
            WHEN INSERTING OR UPDATING THEN :NEW.loan_details
            ELSE NULL
        END
    );
END;
```

Figure 2. Implementation ex.

The code is explained as follows:

- The trigger records the timestamp, the user who executed the operation, and the type of operation (INSERT, UPDATE, or DELETE).
- Additionally, it keeps track of both new and old data for any updates or removals.

Impact: This ensures compliance with financial regulations by maintaining a complete record of changes, which is crucial for audits and investigations.

7.3. Banking System - Preventing Overdrafts

Domain: Banking and Financial Systems

Application: This example addresses a common problem in banking—preventing customers from withdrawing more money than they have in their accounts. Overdraft prevention ensures that no transaction results in a negative account balance, protecting both customers and financial institutions.

Triggers play a critical role here by enforcing account balance checks dynamically at the database level. This eliminates reliance on application-layer validations that might vary across platforms (e.g., online banking, mobile apps, ATMs).

The implementation guarantees the data integrity, by ensuring accurate account balances at all times, a better risk management, by reducing financial exposure due to overdraft errors, and enhancing customers' confidence in the banking system.

Theoretical Foundation: Data integrity requirements that are applied at the database level are used to prevent overdrafts. In database theory, triggers serve as a dynamic extension of constraints, which guarantee that data complies with predetermined guidelines. Triggers provide the ability to implement intricate business logic, in contrast to static constraints like NOT NULL or CHECK.

Economic Consequences: Preventing overdrafts guarantees that financial institutions continue to operate with credibility. Particularly in economies that depend on digital banking, mistakes in this area could result in systemic financial concerns. The organization reduces risk exposure and guarantees adherence to internal and regulatory financial controls by incorporating overdraft logic into the database layer.

```
CREATE TABLE accounts (  
    accountId NUMBER PRIMARY KEY,  
    account_holder VARCHAR2(100),  
    balance NUMBER CHECK (balance >= 0)  
);  
  
INSERT INTO accounts VALUES (1, 'Andrei Ionescu', 5000);  
INSERT INTO accounts VALUES (2, 'Grigore Popescu', 10000);  
INSERT INTO accounts VALUES (2, 'Mihai Ilie', 10000);  
COMMIT;  
  
CREATE OR REPLACE TRIGGER prevent_overdraft  
BEFORE UPDATE OF balance ON accounts  
FOR EACH ROW  
BEGIN  
    IF :NEW.balance < 0 THEN  
        RAISE_APPLICATION_ERROR(-20001, 'Insufficient funds: Overdraft not allowed.');    END IF;  
END;  
/  
  
UPDATE accounts SET balance = 4000 WHERE account_id = 1;  
UPDATE accounts SET balance = -100 WHERE account_id = 1;
```

Figure 3. Implementation ex.

Explanation of the code:

The accounts table structure includes a balance column to represent the account balance.

The BEFORE UPDATE trigger checks if the balance is less than zero before committing the transaction. If the condition is met, the trigger raises an application error.

Outcome: Transactions that would result in a negative balance are blocked, ensuring account integrity.

7.4. Retail System - Automatic Stock Updates

Theoretical Foundation: The event-driven programming paradigm, in which changes in one area of the system cause equivalent updates in other areas, is utilized in this example.

Referential integrity across related tables is crucial in relational database systems, particularly in high-volume transactional settings like retail.

Economic Consequences: Sustaining operational effectiveness and customer happiness depends heavily on accurate stock management. Inventory tracking mistakes can lead to either understocking, which reduces sales and erodes consumer trust, or overstocking, which raises holding costs.

Real-Time Synchronization: Stock level updates are instantly disseminated, guaranteeing that all system parts run on the same information.

Error Prevention: The trigger avoids operational problems like overselling, which could damage a brand's reputation and customer connections, by preventing negative stock levels.

Scalability: The trigger logic ensures data consistency in multi-user scenarios by supporting distributed systems with concurrent transactions.

```
CREATE TABLE inventory (  
    product_id NUMBER PRIMARY KEY,  
    product_name VARCHAR2(100),  
    quantity NUMBER CHECK (quantity >= 0)  
);  
  
CREATE TABLE sales (  
    sale_id NUMBER PRIMARY KEY,  
    product_id NUMBER,  
    quantity_sold NUMBER,  
    sale_date DATE DEFAULT SYSDATE,  
    FOREIGN KEY (product_id) REFERENCES inventory(product_id)  
);  
  
INSERT INTO inventory VALUES (1, 'Laptop Lenovo', 50);  
INSERT INTO inventory VALUES (2, 'Smartphone Allview', 100);  
COMMIT;  
  
CREATE OR REPLACE TRIGGER update_stock  
AFTER INSERT ON sales  
FOR EACH ROW  
BEGIN  
    UPDATE inventory  
    SET quantity = quantity - :NEW.quantity_sold  
    WHERE product_id = :NEW.product_id;  
    IF (SELECT quantity FROM inventory WHERE product_id = :NEW.product_id) < 0 THEN  
        RAISE_APPLICATION_ERROR(-20002, 'Stock level cannot be negative.');    END IF;  
END;  
/  
  
INSERT INTO sales (sale_id, product_id, quantity_sold) VALUES (1, 1, 5);  
INSERT INTO sales (sale_id, product_id, quantity_sold) VALUES (2, 1, 100);
```

Figure 4. Implementation ex.

Explanation of the code:

The inventory table holds product stock levels, and the sales table records transactions.

Trigger Logic: The AFTER INSERT trigger updates the inventory levels immediately after a sale is recorded. If the new inventory quantity drops below zero, the trigger raises an error.

Outcome: Inventory levels are maintained in real time, preventing overselling and ensuring stock integrity.

7.5. Tax Compliance - Automatic VAT Calculation

Domain: Financial Reporting and Tax Compliance Use: In many businesses, calculating taxes is a regulation necessity. In order to ensure consistent and accurate tax application, this example shows how database triggers can automatically compute Value Added Tax (VAT) on each transaction. Businesses with significant transaction volumes, like retail, hospitality, or online marketplaces, will find this extremely helpful.

Compliance: By using an automated method to calculate VAT, companies adhere to tax laws without making mistakes by hand.

Efficiency: By doing away with tedious computations, administrative expense is decreased.

Audit readiness: Produces precise, dependable documentation for audits and tax reporting.

Broader Use: Tax compliance triggers can also be used for other financial indicators, including customs duties in import/export systems or income tax deductions in payroll systems. This illustrates how triggers can handle financial regulations in a variety of ways.

Theoretical Foundation: The concept of derived attributes, in which some fields are calculated using pre-existing data rather than being stored directly, is best illustrated by tax calculations at the database level. This minimizes data redundancy while maintaining correctness, which is consistent with normalizing approaches in database architecture.

Economic consequences: For companies functioning in regulated economies, tax compliance is a basic necessity. Automating the VAT computation process lowers administrative overhead, guarantees consistent execution of tax laws, and decreases the possibility of human error. Additionally, it makes tax reporting easier, which is essential for legal compliance and audits.

Automating VAT calculation using triggers ensures that tax computations are consistent, reducing discrepancies in financial records, simplifies the transaction workflow by eliminating the need for manual tax calculations at the application layer, and aligns with regulatory frameworks, ensuring businesses can generate tax reports on demand without additional data processing.

This approach underscores the importance of embedding domain-specific logic within the database layer, particularly for computations that are invariant across multiple applications or interfaces.

```
CREATE TABLE sales (  
    sale_id NUMBER PRIMARY KEY,  
    product_name VARCHAR2(100),  
    sale_amount NUMBER NOT NULL,  
    vat_amount NUMBER,  
    total_amount NUMBER,  
    sale_date DATE DEFAULT SYSDATE  
);  
  
CREATE OR REPLACE TRIGGER calculate_vat  
BEFORE INSERT ON sales  
FOR EACH ROW  
BEGIN  
    :NEW.vat_amount := :NEW.sale_amount * 0.19;  
    :NEW.total_amount := :NEW.sale_amount + :NEW.vat_amount;  
END;  
/  
  
INSERT INTO sales (sale_id, product_name, sale_amount)  
VALUES (1, 'Laptop Lenovo', 1000);  
SELECT * FROM sales;
```

Figure 5. Implementation ex.

Explanation of the code:

Table Design:

- sale_amount: The base price of the product.
- vat_amount: The computed VAT, which is dynamically calculated by the trigger.
- total_amount: The final amount, including VAT.

Trigger Type: BEFORE INSERT: Ensures VAT is calculated and the total amount is updated before the transaction is saved in the database.

Logic: VAT is calculated as 19% of the sale_amount (customizable based on tax regulations). The total_amount is computed by adding the vat_amount to the sale_amount.

Outcome: The trigger eliminates manual VAT computation, ensuring accuracy and consistency in financial records.

8. Conclusions

This study shows how important Oracle SQL triggers are for process automation, data integrity, and improving operational efficiency in economic systems. The selected examples automatic stock updates, VAT computation, and overdraft prevention - provide useful examples of how database triggers tackle actual issues in banking, retail, and taxation. Triggers offer a reliable, effective, and consistent way to enforce intricate rules and uphold regulatory compliance by integrating business logic straight into the database.

Triggers are incredibly useful despite their seeming simplicity. In addition to protecting data integrity, they enable businesses to concentrate on innovation and expansion rather than ordinary operating issues by automating basic checks and computations. These little scripts carry out enormous responsibilities, guaranteeing that every transaction, stock adjustment, and tax calculation is done perfectly. They stand for a dedication to excellence and the creation of systems that benefit, not harm, humanity.

The examples demonstrate a number of benefits of employing triggers:

- **Real-Time Automation:** By automating repetitive processes like inventory updates, tax computations, and balance checks, triggers remove the need for human intervention.
- **Data Integrity:** Triggers lower the possibility of human or system errors by enforcing rules at the database level, ensuring that data stays consistent across all activities.
- **Regulatory Compliance:** By applying computations or validations automatically and consistently, triggers make it easier to comply with legal obligations, such as tax laws.
- **Scalability:** Triggers' ability to manage activities effectively without sacrificing performance is demonstrated by their use in high-transaction scenarios.

Prospects for the Future

Triggers' adaptability creates new opportunities for application and research. Future research might concentrate on:

- the effects of employing triggers in extremely complex systems on performance.
- extending trigger logic to help with predictive analytics, like estimating inventory requirements by looking at past patterns.
- looking into the use of triggers in cutting-edge fields where real-time data integrity is essential, such as blockchain.

To sum up, Oracle SQL triggers provide a strong way to automate business logic, guarantee compliance, and preserve data integrity in financial systems. The study illustrates how database triggers can spur creativity and productivity across a range of sectors by tackling real-world issues with these examples. The results reinforce the importance of triggers in a quickly changing digital economy and provide a basis for additional research and applications.

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A COMPARATIVE ANALYSIS BETWEEN THE QUALITY OF EDUCATION AND DIGITAL COMPETENCIES IN CENTRAL AND EASTERN EUROPE (CEE)

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Abstract

This article investigates the post-2020 evolution of education quality and digital competencies in Central and Eastern Europe (CEE) in the wake of the abrupt shift to online and hybrid learning during the COVID-19 pandemic. We triangulate comparative evidence from PISA 2022, the Digital Economy and Society Index (DESI)/Digital Decade monitoring, the EU Digital Education Action Plan (2021–2027), and the DigComp/DigCompEdu frameworks to map cross-country disparities in infrastructure, teachers' digital readiness, and institutional capacity. Findings indicate partial convergence across several indicators—particularly connectivity and digital public services—yet reveal persistent gaps in basic digital skills, pedagogical integration of technology, and equitable access, with the southeastern EU subregion lagging behind. Urban–rural divides, uneven curriculum implementation, and insufficient large-scale teacher upskilling remain binding constraints. Methodologically, we offer a structured regional snapshot, then contrast Romania's trajectory with EU averages, and synthesize lessons from the United States and China to highlight similarities (connectivity versus capability paradox) and differences (scale, governance, and industrial digitalization). Policy analysis emphasizes the need for people-centric investments that complement infrastructure: standardized DigComp-aligned assessments, micro-credentials for students and adults, robust teacher training pipelines, and outcome-based funding tied to actual technology use in schools, firms, and public services. We argue that narrowing foundational skill deficits (especially among youth, rural communities, and older adults) is a precondition for translating connectivity into sustained improvements in learning outcomes and productivity. The paper concludes with a practical roadmap that prioritizes equity-oriented delivery, sector-linked upskilling, and consolidated

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governance to accelerate convergence within CEE and position the region for the EU's 2030 Digital Decade targets.

Keywords: Digital skills; DigComp / DigCompEdu; DESI / Digital Decade; PISA 2022; Central and Eastern Europe (CEE); Education quality; Digital divide.

JEL Classification: I21, I28, J24

1. Introduction

The recent years, especially after the COVID-19 pandemic created an intense, emulation, boosting the digital education all around the world. Even if, previously, digital education was recognized, the level of formal recognition of it was highly heterogeneous, leaving the national authorities to allow it or not, entirely or partially. After 2020, most of the educational systems abruptly shifted from classical face to face interactions to an online or hybrid instructional process, highlighting the need for new adapted national and institutional strategies, together with teachers' digital competences. It was a quick and, sometimes, a very costly transition, exposing the strengths and the weaknesses of each and every national educational system. Europe was not different. The overnight change due to the pandemic shutdown, especially in early 2020, forced an immediate shift, changing all the optional digital tools and skills, from recommended to mandatory requirements, for an optimal and effective educational process, all across Europe. In Central and Eastern Europe, particularly, the results of this change have been shaped mostly by three interacting forces: *the pre-existing gap or convergence of the quality of education in comparison with the Europe average, the pace of new digital infrastructure rollout, and the capacity of teachers and educational institutions to adopt the technology from the pedagogically perspective.*

From the methodological point of view, this article compares evidence and data collected from some recognized monitoring instruments and policy frameworks to assess where CEE stands, after 2020, versus the EU median, on both education quality and digital competencies. The key resources which guided this analysis refer to *OECD/PISA 2022* assessment⁶, the *European Commission's Digital Economy and Society Index (DESI 2022)*⁷, the *EU's Digital Education Action Plan (2021–2027)*⁸, *DigCompEdu*⁹, and a recent World Bank working paper on digital skills topic.¹⁰

⁶ https://www.oecd.org/en/publications/pisa-2022-results-volume-i_53f23881-en.html

⁷ <https://digital-strategy.ec.europa.eu/en/policies/desi>

⁸ <https://education.ec.europa.eu/focus-topics/digital-education/actions>

⁹ <https://digcompedu.net/statistici/>

¹⁰ <https://thedocs.worldbank.org/en/doc/a607bb6e3b76d2be0f3db8db34dcf73e-0140022025/related/3EDU-WP-14-Digital-skills-development.pdf>

2. Regional snapshot after 2020: infrastructure, access capabilities and digital skill readiness

After just two years from the pandemic crisis, DESI's 2022 Report documented notable progress across the EU, concerning the broadband connectivity availability and the 5G rollout, with strong improvements concerning the fixed high-capacity networks. But this general positive image was just an overall evaluation for the entire EU region. The gaps are also mentioned in the same report, suggesting that the disparities among EU areas are more than serious. If Finland, Denmark, the Netherlands and Sweden continued to maintain the EU leadership in term of digitalization, other member state like Italy or Greece, despite their initial lack of appetite for digitalization, improved their ranks substantially, by implementing constant investments and reinforcing their national political focus on digital. However, there are still member states, like Romania and Bulgaria, were the digital skill appetite for implementation remained among the lowest scores, at the beginning of 2022.

Specifically, while 87% of the EU population (aged 16-74) used the internet regularly during the pandemic, perhaps forced by the lockdown restrictions, only 54% possessed in fact a minimum set of basic digital skills. The problem to be mentioned is that last year, based on the published data, still a large part of the EU population is not reporting to have and to use the most basic digital skills, even if, though most present jobs, such digital skills are required as mandatory.¹¹

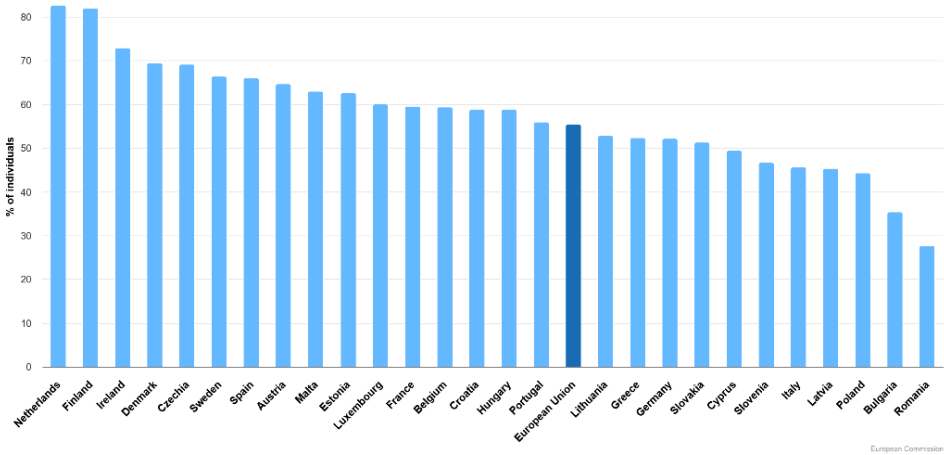


Figure 1. DESI 2025- basic digital skills within EU¹²

¹¹ https://digital-decade-desi.digital-strategy.ec.europa.eu/datasets/desi/charts/desi-indicators?period=desi_2025&indicator=desi_dsk_bab&breakdown=ind_total&unit=pc_ind&country=AT,BE,BG,HR,CY,CZ,DK,EE,EU,FI,FR,DE,EL,HU,IE,IT,LV,LT,LU,MT,NL,PL,PT,RO,SK,SI,ES,SE

¹² https://digital-decade-desi.digital-strategy.ec.europa.eu/datasets/desi/charts/desi-indicators?period=desi_2025&indicator=desi_dsk_bab&breakdown=ind_total&unit=pc_ind&country=AT,BE,BG,HR,CY,CZ,DK,EE,EU,FI,FR,DE,EL,HU,IE,IT,LV,LT,LU,MT,NL,PL,PT,RO,SK,SI,ES,SE

The topmost characteristics to be mentioned here were the general shortage of ICT specialists available on the EU during 2020 and up to 2024, with an inversion trend in the last months, completed with the traditional gender imbalance issue, with only 19% of ICT female specialists in areas like technology and engineering.

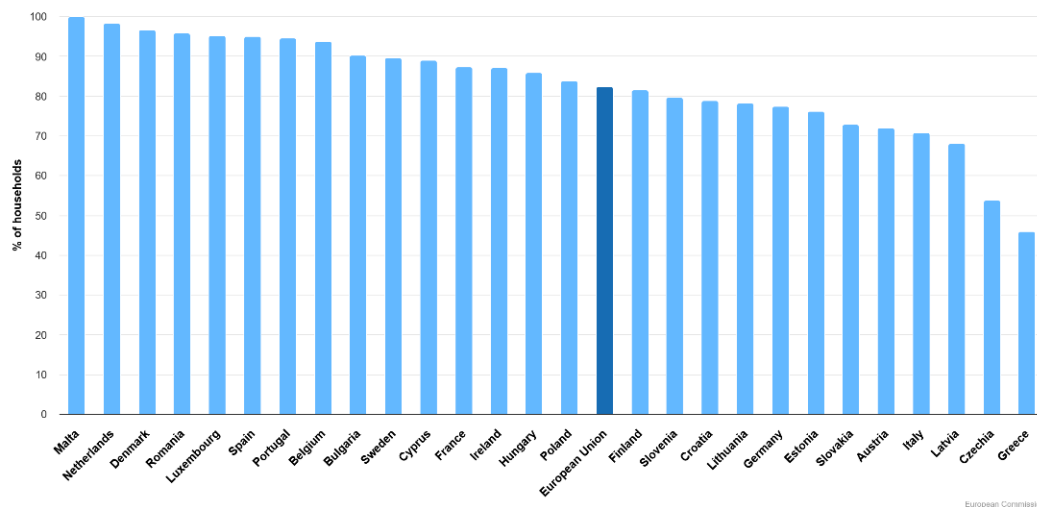


Figure 2. Fixed Very High-Capacity Network (VHCN) coverage¹³

Describing the broadband connectivity, while the EU has reported full coverage of broadband, in fact, only 70% of households can benefit from performant broadband connectivity, with a reported large gap between rural and urban areas, and important differences across nations. For example, if countries like Luxembourg, Denmark, Spain, or the Netherlands are reporting an almost full coverage, in Greece, only 1 in 5 households have access to fixed broadband connectivity. In the same time, countries like Estonia, even if is being reported as one of the best performers in digital services implementation and education based on digital tools, is not among the forerunners, while Romania, one of the poorest performers in the same area of analyses places on the fourth position, proving its inability to use available infrastructure resources.

Based on these facts, we need just to mention one more aspect, namely that, when Covid stroked, only 55% of SMEs reported at least a basic level in the adoption of digital technologies¹⁴. Sweden and Finland have the most digitalized business environment with

¹³ https://digital-decade-desi.digital-strategy.ec.europa.eu/datasets/desi/charts/desi-indicators?period=desi_2025&indicator=desi_vhcn&breakdown=total_pophh&unit=pc_hh&country=AT,BE,BG,HR,CY,CZ,DK,EE,EU,FI,FR,DE,EL,HU,IE,IT,LV,LT,LU,MT,NL,PL,PT,RO,SK,SI,ES,SE

¹⁴ Eurostat, European Union survey on ICT usage and e-commerce in enterprises

reported values around 86% and respectively 82% of their SMEs, while Romania or Bulgaria declared among the lowest rates of having a basic level of digital intensity.

Fortunately, things are changing, and the latest reports and ranks, covering the last four years, are showing us a different image.

But despite all the undertaken initiatives at EU level, the most recent analysis underlines some previous expressed concerns, outlining Europe need to improve its regional and international leadership in digital technologies, knowing that the international market proves to be a very dynamic one, with major players and competitors like US and China. As result, the full potential of the Single Market, from the ICT perspective, remains unleashed. Furthermore, more than 80% of the technologies and services demanded all over EU are designed and produced abroad, in third countries, while the presence of European ICT companies among the world's leading players is still minimal.

Another perspective of the same conclusion is offered by the 2022 PISA results, showing again a very heterogenous mix of systems all over the EU. While some national education systems, like the Estonian one, remains among Europe's top examples, other member states, mainly from the south-eastern EU area, reported notable declines compared with the pre-pandemic years. The results also exposed severe equity gaps and strong interdependences between the national wellbeing and development progress and scholar population' digital competences, suggesting that the gaps cannot be diminished in the absence of strong and sound economic growth and development.

This also means that the pressure applied by the European authorities on each and every national education policy maker, especially in the lowest ranked member states, needs to be constant, otherwise the perspective of economic development stalls, human capital formation disruptions, together with future risk of brain-drain phenomenon and social fragmentation cannot be ignored or even avoided, causing even more important problems to EU responses toward international challenges on its own role as regional leader.

3. Comparative patterns across EU - convergence, divergence, and inequality

As already presented, the available data reports show two facts. Firstly, after accession, the new member states reported accelerated improvements in certain digital indicators, mainly because some new opportunities were available to them due to the new membership and, secondly, the post pandemic opportunities, among them the investments financed by each and every national Recovery & Resilience plans caused faster year-to-year improvement in certain digital indicators, demonstrating a catch-up dynamics.

Despite overall convergence, large gaps are still evidenced within member states and among them. Urban versus rural disparities, advantaged versus disadvantaged educational systems,

socio-economic inequalities among similar family patterns in different EU regions persist and continue to shape gaps in actual digital competence and learning outcomes, despite direct or indirect EU efforts.

The overall quality in national educational systems around member states split Europe into two major categories. Countries that combined clear infrastructure investment with curricular adjustments and human force training reported more educational value acquired through technology implementation. On the other side, all member states, where infrastructure was enhanced but teacher support was absent or minimal, reported some improvements but with overall effects and quality below the forerunners.

Recent adoption of the Artificial Intelligence, changing patterns in offering services from classical ways towards on-cloud delivery, and the large implementation on big data analysis by the business environment has improved the overall national educational systems' appetite for embedding more and more digital competencies, however, EU remains reliant on external providers, making us quite vulnerable to other competitors, like US or China.

With only half of Europeans (55.6%) reporting a basic level of digital competences, we remain vulnerable, while technology advances in other regions, making us more like users and not creators or innovators of these new skills and technologies. The digital transformation, present all around the world, intensified vulnerabilities and inequalities, raising concerns about our capabilities to adequately tackle the international context.

The latest Digital Decade Policy Programme (DDPP)¹⁵ mentions recent improvements across Europe concerning digitalization of public services or basic 5G coverage compared with previous years, but, at the same time, highlights the gaps and the lack of advancements, still present, despite the numerous efforts made to address them.

The Estonian example can be mentioned in this context as among one of the best reported all-around Europe. Its long-term digital strategy is known even before 2020. Estonia is also appreciated for having a public administration strongly based on online communication interfaces with the public, being a performer in what we call e-government. Advanced e-government services, constant investment in digital-ready educational system, constant specialized training for teachers and other categories involved in delivering educational services, resulted in relative resilience during COVID 19 pandemic and created premises for a rapid return, without the educational process being affected in a particularly serious way.

On the other hand, Romania and Bulgaria scored lower compared with EU average in general and Estonia's performances in particular. Policy responses, especially since 2021, have included targeted some specific investments, mainly recovery & resilience allocations for digital and education infrastructure, but with no translation into consistent pedagogical

¹⁵ <https://digital-strategy.ec.europa.eu/en/policies/2025-state-digital-decade-package>

competence, the generated results do not show any significant improvements, placing us at the end of the list.

For EU decision makers, overall raising of both education quality and digital competencies remains an objective to be addressed in the next months or years. Furthermore, the present of these already mentioned disparities between the west and the east will not ease the process.

Future financing programs to be launched at the EU level need to address in this context, both the hardware/servicing area and the professional development of these new competences for teachers and trainers. The metrics used in evaluating the achieved results need also to be adapted in a way to better evaluate the skill acquisition reported by the trained personnel. Embedding digital competencies across subjects during the educational process rather than treating them as an isolated subject will create a real integrative and formative digital environment, capable of being properly assessed.

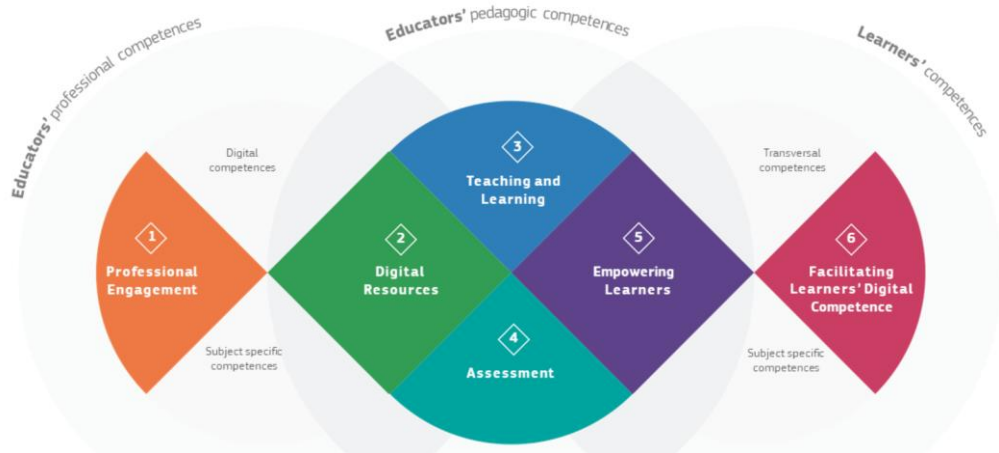


Figure 3. DigCompEdu-digital competences and the educational process¹⁶

The future investments in communication infrastructure need to address more the rural areas and the socio-economically disadvantaged regions, especially in the eastern area of the EU, because the lack of profitability makes these regions to be left somehow behind the urban areas. Or in the absence of good infrastructure, chances for the digital skill dissemination and quality education improvement lags.

¹⁶ https://joint-research-centre.ec.europa.eu/digcompedu_en

4. Digital skills statistics in Romania

The diffusion of digital technologies across sectors has elevated ICT competencies - from basic digital literacy to advanced professional skills - into core determinants of productivity, inclusion, and resilience. The EU's *Digital Decade policy*¹⁷ makes this explicit through two flagship 2030 targets: at least 80% of adults with basic digital skills and 20 million employed ICT specialists, with marked progress on gender balance. Recent monitoring shows the EU is well short of both targets, underscoring the urgency of large-scale skilling and reskilling programs across Member States.

Following the accelerated transformations in the post-pandemic years, Romania still remains significantly below the EU average in terms of basic digital skills, despite notable progress in connectivity and substantial allocations from the National Recovery and Resilience Plan (PNRR). According to the *Digital Decade 2024 report*¹⁸, only 27.7% of Romanian citizens aged 16–74 possess basic digital skills (EU average: 55.6%), while the share of ICT specialists in total employment stands at 2.6% (EU average: 4.8%). Despite exceptional fixed fiber coverage, Romania's lag in human capital indicators continues to constrain the returns to connectivity, e-government, and business digitalization.

Romania has committed substantial public resources (notably through the PNRR¹⁹) to digital transformation, with ~21.8% of the plan fostering the digital transition (investments in cloud government, interoperability, connectivity in “white zones,” and digital skills initiatives). The gap between infrastructure and people-centric capabilities, however, persists, making equity-oriented training and coherent governance of skills policies pivotal.

This section provides a detailed analysis across three levels: secondary education, higher education, and the active workforce (aged 18–64), with a particular focus on territorial and demographic disparities, as well as on the corrective measures currently being implemented [1].

4.1 Romania vs. the EU: the structure of disparities

4.1.1 Basic digital skills and the new DSI 2.0 measurement

Eurostat's Digital Skills Indicator (DSI 2.0), grounded in the DigComp framework, underpins EU-level estimates of “basic digital skills.” The 2.0 revision modernized items and improves robustness of cross-country comparisons. On this measure, Romania's 27.7%

¹⁷ <https://digital-strategy.ec.europa.eu/en/policies/europes-digital-decade?source=post%3A1754433711931621426>

¹⁸ <https://digital-strategy.ec.europa.eu/en/factpages/romania-2024-digital-decade-country-report>

¹⁹ https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility/country-pages/romania-recovery-and-resilience-plan_en

rate signals a large structural gap relative to the EU mean (55.6%) and the Digital Decade's 80% target.

4.1.2 ICT specialists, graduates, and gender

In 2024, Eurostat estimates that ~5.0% of EU workers are ICT specialists (>10 million people), whereas Romania stands at ~2.8% (from 2.6% in 2023), still among the lowest in the Union (only Greece is comparable). Notably, Romania's female share among ICT specialists is relatively high for the EU (about 27%), suggesting potential to scale inclusive pipelines if volume constraints are addressed²⁰.

On education supply, Eurostat's statistical overview of ICT education for 2024 indicates strong employment rates of ICT-educated individuals EU-wide and gradual gains in women's representation, yet cross-country variation remains pronounced. Romania has historically produced a sizeable cohort of ICT graduates relative to its population, but transition into domestic ICT employment is shaped by outward mobility and regional labor market dynamics²¹.

4.1.3. Territorial and demographic divides

Urban–rural divides are salient across the EU and especially pronounced in Romania. EU evidence shows systematically lower above-basic digital skills outside cities; for 2023, internet access remains slightly lower in rural areas, and the largest gap concerns content creation skills. Romanian analyses consistently report lower skills attainment in rural communities, compounding social exclusion risks.

Complementary assessments (World Bank technical assistance and recent Romanian commentary on the Digital Decade) highlight low adult learning participation, stark age and education gradients, and rural disadvantages, despite targeted measures (e.g., library-based digital hubs) financed under PNRR.

4.1.4. Policy capacity and governance

Recent EU monitoring and independent reviews point to implementation risks: fragmented governance, weaker targets than EU benchmarks (including on skills), limited stakeholder engagement, and delays. The 2026 revision of the national Digital Decade roadmap is a

²⁰ <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250708-2>

²¹ <https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=673722>

critical opportunity to consolidate leadership, adopt credible interim milestones, and integrate outcome-based funding for skills²².

4.2 Romania vs. the United States: different baselines, similar structural challenges

4.2.1 Measurement caveats

Romania's EU metrics (DSI 2.0 "basic digital skills," share of ICT specialists) are not directly comparable to the United States' principal sources, which rely on OECD-PIAAC (literacy, numeracy, adaptive problem-solving) and a growing body of digital equity diagnostics (e.g., National Skills Coalition, FCC²³ CEDC). Thus, comparisons should be interpreted as triangulations rather than like-for-like²⁴ [2].

4.2.2 Adult competencies and digital demand

The PIAAC 2023 cycle shows U.S. adults score near the OECD average in literacy but below average in numeracy and adaptive problem solving; about 28% of adults are at Level 1 or below in literacy and 34% at or below Level 1 in numeracy—indicators of foundational skill constraints that interact with digital readiness²⁵.

On the demand side, a landmark analysis finds 92% of U.S. job postings require digital skills, while roughly one-third of workers lack foundational digital competencies [3] - evidence of a sizable "last-mile" skills gap despite near-universal connectivity. U.S. policy is mobilizing significant Digital Equity Act and broadband funds to close these divides, with emphasis on work-based and community-based upskilling.

4.2.3 Where Romania stands relative to the U.S.

Connectivity vs. capabilities: Both countries exhibit a paradox - high or improving connectivity coexisting with foundational skills gaps. Romania's gaps are larger on EU's DSI 2.0, whereas the U.S. shows broad demand-pull from employers that outpaces the supply of digitally capable workers.

²² <https://www.crpe.ro/wp-content/uploads/2025/10/CRPE-Romanias-Digital-Decade-2030-Roadmap-Building-coherence-collaboration-and-accountability.pdf>

²³ <https://www.fcc.gov/sites/default/files/cedc-innovation-access-wg-digital-upskilling-report-06152023.pdf>

²⁴ https://www.oecd.org/en/publications/survey-of-adults-skills-2023-country-notes_ab4f6b8c-en/united-states_427d6aac-en.html

²⁵ <https://primarynewssource.org/wp-content/uploads/427d6aac-en.pdf>

Labor market composition: The U.S. ICT labor market is significantly larger and more diversified; however, Romania’s relatively high female share within ICT roles could inform inclusive design of U.S. pathways, while the U.S. experience with workforce-employer partnerships offers a template for Romania’s adult upskilling.

Adult learning systems: U.S. institutions (community colleges, workforce boards) provide scalable platforms for short-cycle digital credentials; Romania’s policy architecture could adapt analogous mechanisms (micro-credentials mapped to DigComp, modular courses delivered via libraries, schools, and SMEs) already envisaged in national plans.

4.3. Romania vs. China: contrasting scale, state capacity, and measurement

4.3.1 Data limitations and what can be compared

China does not report DSI 2.0-equivalent “basic digital skills.” Public sources emphasize the scale of the digital economy, infrastructure leadership, and state-backed initiatives to raise digital literacy and industrial digitalization. Academic syntheses juxtapose China’s national literacy campaigns with the EU’s Digital Decade, noting progress alongside persistent urban–rural divides. Consequently, comparisons focus on system capacity and outputs, not like-for-like skill rates²⁶ [4].

4.3.2 Systemic features relevant to skills

Digital economy scale and infrastructure: China’s digital economy reached ~RMB 56.1 trillion in 2023 (~44% of GDP), underpinned by the world’s largest fiber and mobile broadband networks and rapidly expanding computing power—conditions that create vast demand for digital skills and pervasive exposure to digital services.

Industrial digitalization and workforce: MIIT reports continued growth in software revenues and the establishment of hundreds of “intelligent digital demonstration factories,” signaling state-driven diffusion of advanced ICT across manufacturing. Such programs are typically accompanied by large-scale, employer-embedded training.

Talent formation: International rankings (e.g., IMD World Talent) show steady improvement in China’s talent competitiveness, tied to increased education spending and the ability to tap large cohorts, though regional disparities persist and external comparability is debated²⁷.

²⁶ <https://www.carecprogram.org/uploads/Mr.-Gang-Zhu-Deputy-Director-International-Economic-and-Technical-Cooperation-Center-Ministry-of-Industry-and-Information-Technology.pdf>

²⁷ <https://global.chinadaily.com.cn/a/202409/27/WS66f6693aa310f1265a1c54c2.html>

4.3.3 Where Romania stands relative to China

Romania's advantage lies in its EU governance framework (DigComp, DSI 2.0, Digital Decade targets) and access to EU funding mechanisms. China's advantage lies in scale, tight policy coordination, and industrial policy instruments that accelerate digitalization in firms. For Romania, feasible lessons from China include: (i) sector-specific (manufacturing, health, public administration) digital upskilling tied to technology deployments; (ii) regional "demonstration" sites that integrate infrastructure, software, and training; and (iii) robust data systems to monitor skill attainment and usage. Translating these to the EU setting requires adherence to EU standards on privacy, transparency, and open labor markets.

5. Root causes of Romania's disparities

In our vision, we consider that the following four elements are the most important and relevant for explaining the current disparities between Romanian population groups, regarding the ICT level of knowledge.

1. Late start and policy discontinuities: Repeated administrative turnover and fragmented governance have hampered policy continuity and execution in digital skills, even as capital investments (fiber, cloud government) moved forward.
2. Education system performance: OECD reviews underline persistent foundational learning deficits (as seen in PISA) and low participation in adult learning, which depress the absorptive capacity for ICT upskilling later in life²⁸.
3. Territorial inequities: Rural–urban disparities in income, schooling, and service access translate into digital skills gaps, despite improving connectivity; "last-mile" social infrastructure (training venues, mentors, employer demand) remains thin in rural counties²⁹.
4. Labor market structure: A relatively small ICT-intensive sector (by employment share) and the international mobility of Romanian ICT graduates constrain domestic pathways, even as the female share among ICT specialists is a notable strength to build upon³⁰.

²⁸ https://www.oecd.org/en/publications/education-and-skills-in-romania_594cbb5d-en.html

²⁹ <https://ec.europa.eu/eurostat/statistics-explained/index.php?oidid=656908>

³⁰ <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250708-2>

5.1 High school level considerations and statistics

Youth data points to a paradox: heavy use of social platforms coupled with low levels of digital literacy. In 2023, only 46% of 16–24 year olds in Romania had basic digital skills (the lowest rate in the EU; EU average: 71%). At the same time, Romania had the highest TikTok penetration in the EU (~47% of the population with an account), which highlights that digital “consumption” does not equate to skills [5].

In standardized assessments, analyses of digital literacy in the Baccalaureate (2020–2022) show statistically significant differences: girls score better than boys, and students from rural areas score significantly lower than those from urban areas; correlations with other tests are of medium intensity, suggesting that digital literacy is associated with overall academic performance. The *Brio Digital Literacy Report (2022)* confirms these disparities and insists on regional differences in digital literacy among students [6] [7].

Structural factors:

- Curriculum: the cross-curricular integration of DigComp in high school is uneven; mandatory "digital skills" modules are poorly standardized at the national level.
- Resources & connectivity: rural–urban gap in access to equipment and quality Internet (although Romania excels at FTTP as an infrastructure, educational use remains suboptimal) [1]
- Teacher training: recent plans announce the training of ~100,000 teachers in digital skills through the PNRR, but require monitoring for scaling and quality [8]

The implication of the above statements is clear - without a coherent “mix” between infrastructure, curriculum and teacher training, exposure to platforms does not transform competence. Interventions should aim for systematic DigComp assessment in high school and differentiated support for rural areas.

5.2 University-level considerations and statistics

At the university level, Romania has high shares of ICT graduates and a relatively good presence of women in ICT, aspects highlighted in the Digital Decade reports; however, generic digital literacy among non-ICT students remains heterogeneous. DESI/DDPP data indicate that ~72% of adults do not have basic digital skills (2022–2024), which also implies the non-ICT university population, especially in the transition to the labor market [9].

Universities have accelerated e-learning platforms and administrative digitalization post COVID, but the mandatory transversal digital skills module is often optional or local.

Analyses on the body of high school students (Baccalaureate candidates) and on the transition to university suggest that the rural-urban gap is "transported" to the university environment, affecting the ability to capitalize on advanced digital resources [6].

Improvement directions:

- Systematic introduction of micro credentials in digital skills for all domains (data literacy, AI literacy, cyber hygiene).
- Partnerships with industry for applied projects that validate DigComp competencies (e.g.: PNRR collaborations, government cloud, interoperability) mentioned in the national DDPP targets.
- Integrating DigCompEdu model assessments at the program level, not just in ICT faculties/schools.

5.3 Considerations and statistics at the level of the active labor force (18–64 years)

The workforce profile reflects the most acute shortage. In 2024–2025:

- Basic skills: 27.7% of the population (16–74) – representative indicator for 18–64 – have minimal digital skills (EU: 55.6%).
- ICT specialists: 2.6% of employees (EU: 4.8%).
- Lifelong learning: adult participation 4.9% (EU: 10.8%), which slows down systemic upskilling/reskilling [10].
- Disparities: only 21% of rural residents have basic skills; at 65–74 years old, 6.17% (EU: 28.19%), highlighting the need for "last mile" programs and human support for public digital services.

In the labor market, employers increasingly require digital and AI skills even in non-IT roles, but only ~40% of employees regularly use digital tools; AI adoption in companies remains the last in the EU, despite increasing demand and workplace training initiatives. In parallel, Romania has made visible steps in the digitalization of public services (government cloud, ROeID, e-invoicing), but the benefits on civic and corporate skills are materializing gradually, requiring digital literacy campaigns and UX simplifications for broad adoption [11] [1] [12].

Among the relevant interventions correlated with the above issues we can mention, for example, The Digital STARs program (World Bank) aims to train 100,000 citizens by 2026, transforming 1,135 libraries into skills hubs; the approach targets vulnerable groups and

reduces territorial inequalities. For the 60+ population (and their families), Erasmus+ DigitalScouts initiatives confirm the need for support networks and community “digital mentors”, complementary to formal courses.

6. Priority directions for Romania (with EU-level alignment)

- Make DigComp the lingua franca of lifelong learning

Adopt and scale a national DigComp-aligned certification (micro-credentials at basic, intermediate, advanced levels) across schools, adult centers, libraries, and employer academies; link to hiring and wage supplements in public administration and SMEs.

This aligns with EU Digital Decade targets and leverages DSI 2.0 for measurement.

- Target the equity gap where the marginal gains are largest

Prioritize rural counties, older workers (45–64), and low-educated adults with community-based delivery (public libraries as digital hubs, mobile labs, school-based evening programs), building on PNRR investments already earmarked for “white zones” and local hubs.

- Tie training to actual technology adoption in firms and agencies

Couple grants for cloud/AI/data adoption by SMEs with mandatory digital upskilling hours and outcome audits; replicate China’s “demonstration factory” logic in an EU-compliant manner through regional digital sandboxes and shared trainers.

- Strengthen governance and accountability

Consolidate a single ownership point for digital skills (cross-ministerial unit), publish annual outcomes (attainment, usage, wage effects), and align national milestones with the EU’s cooperation cycle; address critiques regarding weak targets and fragmented execution.

- Expand work-based learning pathways

Borrow from U.S. practice: employer partnerships, short-cycle credentials embedded in jobs, and sectoral training funds; link to tax incentives for firms documenting skill gains and productivity effects.

Taking into account all the considerations we have emphasized previously, we think that a realistic successfully implemented roadmap for Romania should show how success would look like by reaching the following landmarks:

- Foundational skills: Raise the share of adults with basic digital skills to the EU average trajectory (mid-40s percent by 2028 on DSI 2.0) with credible year-on-year increases, on a path toward $\geq 60\%$ by 2030, acknowledging the distance to the EU's 80% headline.
- ICT specialists: Lift Romania's share toward $\geq 3.5\text{--}4.0\%$ of employment by 2030 through retention of graduates and sectoral expansion, while preserving or improving the female participation advantage.
- Equity: Narrow the rural–urban gap in above-basic skills by at least one-third relative to 2023 baselines, verified via Eurostat regional indicators and national microdata.
- System integration: Full operationalization of DigComp-aligned credentials in secondary, tertiary, and adult learning; outcome-based funding tied to usage (e.g., eID, e-health, tax filing) and workplace application (e.g., ERP, cloud, AI tools) to ensure skills translate into practice.

Cross-country comparison of “digital skills” is complicated by divergent definitions and instruments. EU's DSI 2.0 is behavior-based and DigComp-aligned; OECD-PIAAC assesses cognitive competencies (literacy, numeracy, adaptive problem solving) rather than digital behaviors; China emphasizes economic scale and industrial digitalization with fewer internationally harmonized skills indicators in the public domain. Accordingly, the comparative statements above triangulate across multiple sources and should be read with these caveats in mind.

Nevertheless, if we continue to compare Romania's situation to its main geographically relevant entities – EU, USA and China – we can list the following takeaways:

- Romania vs. EU: Romania's principal challenge is foundational (basic digital skills) and structural (low ICT employment share), not infrastructure. EU frameworks provide clear targets and monitoring, but national execution must accelerate and be equity-focused.
- Romania vs. U.S.: The U.S. balances vast demand for digital skills with significant foundational deficits across adults. Romania can draw on U.S. models of work-based digital upskilling, while the U.S. can learn from Romania's female representation in ICT roles.
- Romania vs. China: China's scale and state coordination speed diffusion of advanced ICT; Romania should adapt the sector-based and demonstration-site logic to EU norms, using PNRR and cohesion funds to ensure the people side (skills) matches infrastructure and software roll-outs.

7. Conclusions and policy directions

In order to start fixing the current issues as fast as possible we discern three elements that Romania can implement on a fast pace approach – each one addressing a different target group:

1. High school level: national standardization of DigComp assessments, sustained teacher training (monitored by quality indicators), and dedicated resources for rural areas (infrastructure + content).
2. University level: cross-curricular micro credentials in data/AI literacy, partnerships with industry for competency validation, and program-level DigCompEdu audits.
3. Workforce level: incentives for upskilling (digital vouchers, tax deductions for training), onboarding campaigns for digital public services, and local hubs (libraries, "one stop shops") for basic skills.

Without accelerated growth in digital skills in the 16–24 and 18–64 segments, Romania risks widening the gap with the EU average even if the network/hardware infrastructure remains competitive (FTTP/VHCN). Focusing on quality of use (not just access) becomes a priority for educational and economic convergence.

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THE CONSTRUCTION OF POWER THROUGH LANGUAGE IN ONLINE NEWS MEDIA – A CASE STUDY

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Abstract

This paper sets out to analyze how power is constructed through language in the Romanian news media, resorting to this purpose to a case study of the online presence of a prominent trust, Antena 3 CNN. More specifically, we are looking at the titles/headlines of the antena3.ro news website homepage, as they appear at a certain moment on the 21st of October 2025, in a snapshot of the page taken at a specific time mentioned in the presentation below. We start from the assumption that media is a powerful instrument in society, shaping power perceptions and management at various levels, which this analysis intends to demonstrate, power being more than the one distributed and attributed formally and openly to institutions and actors through the actual discourse and concrete messages of the content under scrutiny. In the body of the research, we start from lexical choices to depict how state actors are introduced as holding power, how conflict overrides the social scene both nationally and internationally, in visible and subtler ways and at more levels, and how the authority of the official agents is questioned due to failure to provide for the citizens, negative labels being assigned to them implicitly through the depiction of their bad performance and unseriousness. Gender issues are also transparent through a power interest lens, pointing to the assumption of the Romanian society and culture as a traditionalistic one. The study also investigates the presence of a poignant emotional component in the way in which news is rendered, revealing some of its functions and effects. Considerations on the journalistic style at hand follow, while the conclusions summarize the findings. The method is discourse analysis and cultural studies.

Keywords: journalism, news media, power, discourse analysis, culture

JEL Classification: H5, Z10

1. Introduction

In the context of the 2024-2025 events in the social and political landscape in Romania, power has become, once again, a relevant point of discussion. The annulment of the elections in November 2024, with the contested figure of Georgescu and the accusations

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brought to him, the assumption (at the time) of hybrid war and insidious influence of obscure state and non-state actors – as they were called initially – then the corresponding decision-making of high institutions and authorities, the subsequent vote for democracy and constitutionality embodied by the governmental Coalition and its contested performance afterwards have all made the notion of power central to people's mental atmosphere, as well as open for debate. Power has been denied, taken away, granted, entrusted, and these days it is highly contested. Freedom of speech provides the means to construct and reconstruct social entities and actors in terms of their empowerment in a very fluid manner. In the context of various crises, power is much less fixed, it shifts rapidly, and it leaves one place as soon as it has been attributed there, seeming a more versatile than usual reality that has become impossible to grasp and predictably get hold of.

Active and investigative journalism uncovers realities and reveals them to the public, talking about them openly and immediately, and, as these realities are unpleasant and involve unveiling corruption among authorities as well, distrust of the population in them is an immediate effect, which contributes to power being contested and seen as highly dynamic. That is because the placement of power is also a matter of trust and willingness to cooperate with the one holding it formally, and this willingness is lost once the bodies and institutions that are theoretically supposed to act ethically and even ensure justice are deemed and/or proven as less than ethical. In this situation, those unveiling facts to the public have a power of their own, and their perspective and rendering of information creates modes of power distribution as well, which leave an imprint on the collective consciousness – a way of dealing with power itself – raising awareness (yet another type of power) and giving power back to the audiences to exert it in their turn back on politicians and others through activism and votes. Journalism also puts pressure on those formally holding power, in a turning of tables type of situation, sometimes determining and speeding up the taking of steps and measures. Hence, the interplay of power is complex, and in our context starts with having knowledge and acquiring and exercising a voice.

We are interested here in performing an analysis of how power is constructed through language in the headlines on the Antena 3 CNN online news website (antena 3.ro) homepage on a random day, which in our case is the 21st of October 2025, based on the way the page was at 5:20 p.m. We need to state the fact that power is understood not only in the limited sense of the institutions that officially and formally hold it, as their mere mention in the news is just part of our interest, but also as how authority, agency, control, dominance, and resistance are linguistically and discursively produced and what the implications of this manner are, socially and pragmatically. Hence, we are looking at how power is constructed in all the ways that we have mentioned above. We mean to investigate what the specific way of introducing the facts connotes socially, based on lexical, semantic and pragmatic insights. The approach is discourse analysis and cultural studies.

2. Analysis

To the aim introduced above, we start by considering as samples the first ten titles that appear at the top part of the page. Since Antena 3 is a Romanian news website, the headlines are in Romanian, but are provided below as English translations. These constitute a starting-point corpus for the research, but this study considers the whole of the announced text bits on the homepage.

- 1) Sources: Scandal in the Coalition over magistrates' pensions. PSD got angry with Bolojan and left the government meeting
- 2) The Coalition has decided on the date for local elections in Bucharest. Nicușor Dan's successor will be elected on December 7
- 3) Daniel Băluță on a possible candidacy for mayor of Bucharest: "I am thinking about it very carefully."
- 4) The Superior Council of Magistracy praises the Constitutional Court's decision to allow magistrates to retain their privileges: "It reaffirms the role of guarantor of the independence of the judiciary."
- 5) Russians reject Trump's proposal for Ukraine. Lavrov: "Ceasefire means Ukraine remains under Nazi regime"
- 6) The 30 trains suspended on Tuesday resume service. CFR announces that an agreement has been reached on debt repayment
- 7) Magistrates give up protests and announce that they will judge "all cases" after the Constitutional Court decides to maintain privileges
- 8) Russian sabotage operation on Romanian territory. SRI catches two Ukrainians, coordinators of Russian services, who were preparing attacks
- 9) "Russia's suicidal attempt to advance in Zaporizhia was a massacre." Huge losses for Putin's army after the latest assault
- 10) Mircea Badea's harsh message after the explosion in Rahova: "This is not a country, it's a carnival. You're surprised it still exists." [1]

We shall start from concretely looking at language use in the statements above, as well as then extend our attention and the notes to others on the page. We will take into account the lexical content, syntax and morphology and derive some insights based on these. Starting with the basic units that are lexical, we first notice the prevalence of the use of common nouns that have become proper ones because they have been arranged in various groupings to constitute names of bodies and institutions: the Coalition, the Superior Council of

Magistracy, the Constitutional Court, PSD, CFR, SRI. For instance, the Coalition refers to the reunion of the democratic parties that have officially agreed to govern together. The use of acronyms shows that the readers are supposed to have some kind of general knowledge of social and political life, as the abbreviations denote judiciary forces, intelligence services, parties and the national railway transport company, all of them functioning inside the country. There are other, proper nouns present in these headlines. Some of them refer to Romanian personalities: Bolojan, Nicușor Dan, Daniel Băluță, Mircea Badea, most of whom are public figures occupying various offices in our country – the Prime Minister, the President, the mayor of district four, in this order – the exception being Mircea Badea, who is a well-known political satirist, media critic and television host in Antena 3 CNN. Others are foreign personalities, such as Trump, Lavrov, Orban, Putin, who are heads of states (Trump, Putin), the Russian Ministry of the Exterior (Lavrov) and the Prime Minister of Hungary (Orban). Then, there are the names of the countries corresponding to these personalities, with the addition of Poland and Ukraine lower on the page. What we notice from these is that the foreign affairs news items center on the war between Russia and Ukraine, and how other actors make efforts to either prevent it from escalating or/and stop it, as well as safeguard the states of the NATO alliance and the inside status and protection ensured by it for them in case of escalation of conflict (see the news on Poland's comments on Putin being on a flight over its territory). This issue of war, then, is considered relevant and presented as such, given its prominence on the page, creating a sense of urgency and even fear, since the implication is that it is threatening to our country by its geographical proximity, which justifies the importance that it is granted in the economy of the homepage. Overall, however, the news on problems and issues inside the country prevail over the external ones. The numerous references to bodies and people holding power officially prove the preoccupation and concern with power overall, as these pieces of news hold primacy over others, appearing in the Main Columns section at the top of the homepage. They are also written in a larger font; hence, their positioning on the page, the font size and buzz words are meant to highlight concern with power and draw the readers' attention to this concept both consciously and subliminally.

Common nouns and noun phrases included in the most visible titles above refer to people or groups of people holding power (e.g.: magistrates, the government, successor, mayor, guarantor of the independence, the judiciary, coordinators), and to actions that involve dealing with power, attributing it and/or decision-making (e.g.: local elections, candidacy, decision, privileges, independence, proposal, regime, debt repayment, operation, attacks, massacre, army, assault, carnival). The presence of some terms referring to military operations introduces aggression in the linguistic landscape in an explicit manner, depicting mass violence and abuse. The reality of war has already been hinted at through the mention of the personalities involved in it as conflicting parties, collateral parties that may be affected or drawn in at some point, or negotiators for peace. In the enumeration of common nouns above, there are also emotionally charged terms that amplify this ingredient of

aggression, such as “massacre” and “scandal”, which create a sense of tension, stressing the existence of conflict at more levels, of actual physical clashes, as well as verbal and ideological ones. The use of the term “privileges” stresses power inequality and hints at potential abuse of power; moreover, its frequent use for a few times is meant to function as a constant reminder of these concepts and fuel frustration, the word becoming an enhancer of what is perceived by the population as social injustice. This idea and already-planted impression is naturally continued and amplified while resorting to noun phrases connoting moral condemnation and framing: “Nazi regime”, “carnival”, and then, lower on the webpage, “power excess”, “double stupidity”, “chaos”, which are inflammatory, as they suggest implicit unethical and immoral courses of action, hence picturing certain actors as fallen, falling and failing in their duties, as well as overreaching, morally suspect and thus corrupt and abusive.

Coming back to the notion of conflict, we can summarize then, based on the aspects stated above, that it is both denoted and connoted at more levels. There is, first, the material, armed conflict of war, at international and even global level, as suggested by news of territorial disputes and negotiations between Ukraine and Russia. Then, there is internal conflict, at national level, manifesting as disagreements inside the Coalition, as well as between various authorities, an example being the Coalition’s resolutions clashing with the CCR’s. Besides bodies being in antagonism, there is animosity between individuals who are prominent public figures, such as Bolojan and some leaders of PSD, the suggestion being that conflict is triggered not only by contrasting views on specific points that require decision-making, but also unspecific, more obscure ones, based on vested collateral interests and spheres of influence that are not directly related to the issues at hand, or even on personal matters – hint present in the formulation “PSD got angry with Bolojan”. There is, moreover, an underlying conflictual or tense state between the authorities and the population, based on and fueled by (assumptions of) corruption, faulty *modus operandi* and shady, difficult-to-explain or suspicious-looking actions, as well as the authorities not doing their job. This creates distrust between the state and society, the people who are impacted by the decision-making of the former entities.

The use of the noun “carnival” has rich connotations. It is employed in relation with the incident of the explosion that happened at a block of flats from Rahova based on a gas leak in the basement, which raises questions – and eyebrows – based on the assumptions of either faulty performance of Distrigaz or faulty legislation preventing a logical course of action in this case. Here, the authorities are suggested to be guilty in one way or another, as this kind of event should not be possible in a civilized country in which the state and bodies are doing their job. Apparently, Distrigaz could not do more than stop the gas supply and seal the outlets, as the law does not allow any taking of action from the company’s part, so the state authorities have not discovered this logical contradiction or the need for further regulation of such a context beforehand. As days have gone by from the accident, ANRE’s attributes also have come under scrutiny, to check whether its role was fulfilled and

irregularity could be related to this body as well or not. Coming back to the term of choice, “carnival”, historically, the carnival period preceding Lent refers, as early as the Middle Ages, to a suspension of the ongoing order for a period of time, during which a denial of all norms and rules takes place. Authority is paused, and disorder becomes the overarching principle instead. Medieval accounts of this period mention excess eating, the loosening of instinctive drives, and violent acts manifest in gang clashes such as the “bridge battles”, beatings, and even murder [2]. Also, during carnival, the use of masks obscures the identity of the actors involved in the event, thus also lifting the weight of responsibility for any damaging acts off the entities involved in any potential wrong-doing, harm or lawlessness [3]. Carnival is therefore a celebration of freedom understood in the pejorative sense of the phrase as well. The alternative world that carnival represents is one in which relationships are formed on the principle of the marketplace, i.e. of negotiation of status, of fluidity, informality and reinvention [4]. For more than one reason that we have just mentioned, carnival is a place of transgression and reinterpretation of boundaries, of the questioning of order as we know it or as it is normally understood. We have insisted a bit on this concept, looking at its roots and theorization throughout history, because its complex meaning traits are meant to be transferred to the authorities in our country, suggesting a dysfunctional or malfunctioning state. For the knowledgeable, Badea sends to all the interpretative content described above through the use of the concept of carnival, which he synthetically means to connote, accentuating precisely chaos and lawlessness. His intention is to imply the dystopic quality of our country as a space, which constitutes severe criticism with respect to the state. Disempowerment and lack of action from the part of the responsible bodies create powerlessness for the citizens. In discourse, the idea of accidentality associated with the tragic incident, is also suggested to characterize the officials, through their indifference, carelessness and incompetence (see the phrase “double stupidity”), which result in people’s helplessness and in an overall feeling of everything being random or the result of chance – hence, Badea’s contention that it is surprising that our country goes on at all. The feature of being inactive leads to dark scenarios. It also stands in opposition to the suggestion of dynamism when it comes to having vested interests hinted at above, in the construction of conflict as prevailing and dominating the political-social scene. In other words, the authorities are passive only when it comes to the citizens, but can be active in support of obscure interests or to antagonize one another. This creates, overall, the impression of corruption in the system. In support, validation and reinforcement of the ideas to which the notion of “carnival” sends, the noun “chaos” is used in another headline, referring to the cancellation of dozens of train trips causing agglomeration in railway stations and distress to those who only found out about them as they were already on the platforms, preparing to embark on the respective trains. Moreover, the word “chaos” gets repeated in another headline in the same segment of news, on the middle column, immediately to the right of the headline that we have examined, which strengthens, visually as well, the message conveyed above.

So far, a certain dysfunctionality of the system of the state has been suggested, along with passivity, carelessness, and lack of know-how and incompetence. However, state action is also depicted as hostile to the population in some announcements. One title reads “The city hall has increased the tax by 500% for several owners of dilapidated buildings in District 1 of Bucharest.” [5] The juxtaposition of the percentage, which is written in numbers rather than letters to maximize the impact of the figure, and the adjective “dilapidated” create an oxymoronic, blatant opposition, to point out scandalousness and illogicality and engender outrage against the officials, revealing their decisions as lacking common sense, and even as not making sense at all. This piece of news is placed right above the one using the phrase “double stupidity”, which appears next to the noun “populism”, the latter implying a desire to gain the benevolence of the masses, but also an intention to do so undeservedly, as part of a strategy to dupe or deceive.

If we analyze how state actors appear in the headline statements, these are depicted as active agents, powerful and uncontested. This impression is also rendered by the use of strong action verbs in relation with them, which are assertive, in the declarative mood, presenting statements as facts, the strong assertiveness contributing to an impression of definitiveness and authority. The state actors appear as holding the reins and being doers of actions, dynamic and efficient in making decisions, quantitatively (but not necessarily right in them, i.e. qualitatively). As pointed above, they are hinted as active in an abusive manner, deciding for the citizens without really representing their interests. When it comes to the interests of the population, the authorities are rather depicted as uninvolved, careless, unprofessional, incompetent and even ill-intended. The verbs that illustrate these statal entities’ behavior are “decided”, “reaffirms”, “announces”, “will judge”, “catches”, “has increased”, “threatens”, “will arrest” (“Poland threatens Putin with arrest/that it will arrest Putin if he enters Polish airspace on his way to Budapest”), “extends”, “can govern” (“Hungary extends state of emergency by six months, citing war in Ukraine. This allows Orban to govern by decree.”) [6] They denote domination and control. The number of occurrences also plays a role in the impression of power; for instance, a verb like “decide” appears many times on the webpage. Also, the tense is most often the present simple or the future, more rarely the present perfect and only accidentally the past. This is indeed a common journalistic feature, linguists attesting to this specific use of the present simple, known as the “historical”, “dramatic” or “narrative” present, to render facts [7]. The news items are thus made “fresh and vivid” (in Hamdan and Qais’ phrase) and become attention-grIPPING [8]. This technique helps news be “more exciting, fresh and immediate” [9]. The targeted effect, besides catching and retaining one’s attention, is making one feel connected, and, on the part of the journalists’ team, seeming professional and up to date with the latest events. There is a violent strain in the way the state actors mentioned above behave as well, mirrored by verbs such as “got angry”, “left”, “hits with a sledgehammer”, or emotionality/whimsicality, in “praises”, indicating aggressiveness and abuse, but also temperamentality hinting at unprofessionalism [10]. The infrequent use of the passive voice

is good from a power perspective, because this means there is no tendency to reduce agent visibility. The preference is for the active voice, to keep agents visible and strong. This also denotes professionalism, and completeness of information, from a journalistic point of view.

Non-state actors are less impactful; they are rather sufferers of actions than the ones performing them. This impression is given using state verbs and the passive voice. For example, the news headline of an incident regarding a wedding in Iran depicts the women involved as docile, describing their states, and not as agents, but as experiencers: “Their bride is in the palace, ours is in the ground.”; or, related to the same news, “Fury in Iran. While women are forced to wear hijab, a high official got his daughter married in a deep-cleavage dress” [11]. We notice the verb “be” describing a state of the respective women, and the passive form bearing on very personal matters, such as one’s clothing style and marriage, which are nevertheless outside the women’s control, decided upon by someone else. One may think that this is the case because of cultural traits, when it comes to a profoundly patriarchal country such as Iran. Let us examine other titles bearing on women who do not pertain to such markedly conservative environments, to see if the passivity changes and was only due to the cultural-geographical context. One headline informs that a seventeen-year old (Romanian) young woman “who fell with the floor two stories, is being operated on her spine”, so we have a verb denoting the suffering of an accident followed by one in the passive voice; another title says that “Mădălina is 17 and she has disappeared for a month” (in original, a passive form indicating her state of being unaccounted for is used); “An OnlyFans star who earns \$13 million a year surprised her fans. What photos did she post?”; “Mother of four reveals an essential daily ritual that has helped her avoid burnout”; “Jennifer Lopez has been accused of infidelity by her first husband. ‘The problem is you. You have been married four times.’” [12] If we look at the last three entries, we notice a few facts. Even the actions of a renowned international star, such as Jennifer Lopez, are framed within a passive construction, but this passivity is doubled by other elements to make her seem deprived of power. She is presented as subservient to a male authority judging her – her ex-husband – who is in a position in which he makes claims and holds her accountable for something (while, moreover, they no longer form a family), so there is clear gender imbalance in terms of power, the man holding the upper hand. Moreover, he passes judgment on his former wife, labelling her in calling her a “problem” and implicating that she has been superficial – to say the least – since she has been married more times, which is a sexist attitude. A hint to potential frivolity in romantic involvements is present in the “OnlyFans” piece of news, in which a woman is implied to be a predator, hence being active and empowered comes with the pejorative connotation of being manipulative, easy or/and dishonest. The dress worn by the bride in Iran is too revealing, which also highlights a sexist assumption that women wearing this kind of clothes are frivolous, on the one hand, labeling it as negative, and, on the other, that women should be more traditionalistic, which is also a form of shaming. The mother’s

resourcefulness saves her from being overwhelmed by her situation, so she is first presented as almost incapable of dealing with her reality. If we sum up, there seems to be a tendency to provide news which depict women as victims, a subordinate gender, powerless or in predicaments, the exception of agency being when they use their appearance or charms to deceive and obtain leverage and advantages inappropriately. This indicates an underlying presupposition that the readers and the country in which the news items are released is thought to be rather conservative, buzzable by this type of content relying on traditional views of gender(s). Romania is perceived, implicitly, as a mainly patriarchal culture. Resorting to posing women as victims or something related to a sexual predator when agents is also meant to strike emotional chords – of compassion and perhaps, respectively, outrage, which increases the involvement of the reader in the material (s)he is reading. This turns out to be a marketing feature.

There are other features that are meant to skyrocket the emotional component and response. One is the use of irony or even sarcasm. Mircea Badea's comment on how the country has come to resemble a carnival due to lack of involvement, care and professionalism of the authorities, which all create an unsafe environment for the citizens, insecurity, danger as well as disorder is seconded by one by Mugur Ciuvică, leader of Grupul de Investigații Politice (GIP) and journalist, who states that "After a month of prevarications, 4 musketeers from PSD wind up detecting unconstitutionality" [13]. We are safe to say that his comments are on the side of sarcasm, and a linguistic analysis proves it. First, mockery is present in the choice of terms in his statement, both nouns and the verb. He refers to the PSD representatives as the four musketeers, in a mocking way to draw a parallel with the heroic acts of the fictional characters, but in reverse, as the deed in this case is not heroic at all, but – the suggestion goes – only adversarial, counter to evidence and thus to normality, in the sense understood by him. The association of the respective personalities with the characters oriented towards performing good deeds for others is comical, since the underlying implication is that they are opposing public welfare, and becomes not only a form of criticism, but a jeering parody. He associates the real-life persons with the well-meant heroes in order to point to the former being the exact opposites of the latter in terms of core personalities. The term that Ciuvică uses to describe the action taken by the PSD representatives is – in Romanian – "tărăgănări". This poses a choice problem to translate into English, because the semantic content in the source language contains the features of [+delay] and [+intentional], so simply using "delays" for it in the target language would not cover all the meaning traits. Additionally, the larger context of the statement obviously sends to intentional, bad-faith delay, which makes the necessity to find a stronger, more accurate term to translate it even more pressing. A word such as "stalling" would cover the intention, but it loses some of the impact through the fact that it is singular (and the Romanian plural form adds momentum and dramatic content), as well as fails to render the action as ill-meant, a supplementary meaning trait implied in the wider context. Hence, a noun like "prevarications" seems to serve the function better, as it contains the features of

insidiousness and deception intent that is not done blatantly, besides the feature [+delay] or [+repeatedness]. As far as the verb is concerned, the Romanian “se trezesc” implies unexpectedness, something that happens out of the blue and thus somehow unfoundedly. What is hinted at here is that there are no real grounds for the conclusion of the four actants. The irony/sarcasm in these comments overall suggests a lack of respect for the people holding power, distrust in their honesty and good intentions, as well as, implicitly, a crisis of authority that may ensue once the public feels this way.

Other kinds of emotions are raised through a reference to the bear Baloo, captive in Straja, and the appeal to save it from the children who poke it with sticks. Helplessness – in people, especially women, which we have already discussed above, is reinforced through this article by a depiction of helplessness in animals. The latter is somewhat more poignant, as animals appear as being at the mercy of people more, generally speaking, and thus doubly defenseless, abuse against them seeming more brutal and raising pity. We may consider that animal abuse is a separate and somewhat more emotionally impactful type because of it. Besides captivity, so being outside the natural environment where an animal feels at home, the bear in question is also suffering violence inflicted by the beatings.

Fear and/or worry is also meant to be triggered by reading the news on this homepage. Weather changes and extreme phenomena are a worrisome theme these days, creating panic and being extremely topical in some circles and cultures. The Americans are particularly interested audiences when it comes to this subject, being sensitive to and fond of it as a nation. The factual aspect that fuels this concern is that the “U.S. faces more frequent extreme weather events”, and there is ongoing anxiety that people are not aware enough of it and the government is unprepared to keep the pace with reality, while official bodies sound the alarm [14]. However, the public is increasingly conscious of the existence of this problem: “Americans who think global warming is happening outnumber those who think it is not by a ratio of more than 4 to 1 (69% versus 15%)”, with 65% being “somewhat worried”, while 48% believe that they “are being harmed by global warming ‘right now,’” according to a national survey jointly performed by members of the “Yale Program on Climate Change Communication and the George Mason University Center for Climate Change Communication” in May 2025 [15]. Given these figures that clearly point to public interest, the competent bodies still feel that it is not enough, which points to the topic of climate change having become a national craze. In other parts of the world, such as on the European continent, increased awareness is visible in the steps that are being taken in the EU and the discussions regarding climate neutrality by 2050 in official forums.

To sum up some of the findings above, we have detected the use of irony, animal cruelty depiction, the portrayal of women as victims, tricksters or predators based on their charms, and the approach of extreme weather as a buzz topic for worry. All of these are emotionally charged and triggering topics. The potpourri of emotions that these give rise to is meant to cover as many dispositions as possible: despise, compassion, outrage, fear, revolt. This

approach ensures that attention is piqued, kept, and increases the involvement of the reader, making it more personal and thus ensuring attachment to the reading of news. A more dramatic presentation of facts determines an intensified attachment to the respective media representatives from the part of the audiences. It may also show, to do the journalists justice, a more involved attitude from their part as well, a desire to uncover truths and to present them to the public as they are, as well as an interest in staying connected to one's readers and audience. Powerful, evocative adjectives serve the same function: "powerful", "lethal", "captive", "serious", "major", "invaluable", "huge", "best", "fascinating", "vital", "strategic" etc. All of them have an augmenting effect, hyperbolizing facts. They thus create the impression that everything that is being presented is highly important or "big" as well, magnifying the relevance of the events, along with the impact that the news items have on the readers. One could say, on the negative side, that, in some cases, things get blown out of proportion, so that the reader may get the feeling that everything (s)he reads about is, metaphorically, apocalyptical. If one follows the text closely, there is a preference for some of these adjectives, which get repeated, such as "powerful" or "major". If we take into account the fact that these accompany the nouns and verbs mentioned above, which already have an inflammatory effect, then the resulting image is indeed almost apocalyptical. The overall notion that we get is the existence of a profound, generalized crisis and conflict.

Stylistically, we notice the recourse to oppositions and binary structures. In the examples analyzing terminology at the beginning of our study above, there are oppositions highlighted on the international arena which is a war theatre, between states (Russia and Ukraine, Russia and the United States), personalities (Zelenski and Putin, Trump and Putin) etc.; in our country, they are presented as existing inside the Coalition, so the governing forces, between both parties and individuals; between the authorities and the citizens, as the decisions of the former seem to work against the interests of the latter (the city hall and flat owners, Orban and the population in Hungary, once he is governing through decrees, Iranian law and customs and the population, as well as wealthy, privileged Iranians – and their possibility to circumvent traditions – and the less fortunate masses), the EU regulations for drivers getting stricter, EU failing to ensure drinking water; populism and the Constitution. Some of these parties are in open conflict, as pointed out above. Conflict is the dynamic between the respective parties, whereas the oppositions that we are mentioning here are created stylistically through syntax in the discourse. Of course, the actual state of conflict between the parties favors their placement in antithesis stylistically, and provides the best opportunity to present the message through this lens. These oppositions intensify and dramatize power struggles.

Directness and indirectness play a very important role in journalism and the construction of power. Declarative mood statements contribute to clarity and placement of power on the authorities, depicted as empowered agents, as exemplified above in this paper. Passive voice is sometimes used to refer to other entities that are usually presented as disempowered or downright victims (citizens, women etc.), and the passive constructions serve rather this

function of showing deprivation of agency than that of obscuring the actual performer of the action. Hence, passivization is not a means of hedging. Directness is generally the rule in the journalism that we see on this homepage. Quotations are another way to achieve it, as statements from empowered personalities are given in inverted commas. They introduce more voices in the discourse, leaving the impression of dialogue, accuracy, objectivity and professionalism. Indirectness is not resorted to, as, from a grammatical point of view, for instance, there are almost no conditionals and modals that would theoretically contribute to fuzziness, introducing hypotheses and uncertainty in various amounts. Hence, hesitation, caution, dodging or evading are not present. The only element that builds indirectness is the indication “Sources”, attached to certain news. This way of forwarding some pieces of news creates for the reader the feeling that (s)he benefits from a heads-up from the journalists, being the first to find out about something, having an advantage because (s)he is part of the audience of the respective media source. For the journalists, it creates the aura of thorough, relentless researchers who, as a result of their assiduous work, access hidden, difficult-to-get-to information. This technique is therefore empowering for both parties, who communicate between them inside info, as one has enhanced capacity to unveil secrets and behind-the-scenes insight, while the other accesses it more quickly. This is also a powerful binder, creating communion and community. As additional layers of meaning go, it can hint at a bit of self-praise when it comes to the journalists, as well as, in the idea of something being hidden from the eyes of the public, to lack of transparency.

Short-span temporality is created through the use of the adjective “breaking” before the news, the mention of how long it has passed from the moment the news was posted, which render the impression of recentness, but also immediacy, urgency, of something unfolding as we speak, and of pressure and stress, as actions are taking place in an ongoing manner, and one has to keep up in keeping oneself posted.

3. Conclusions

The journalistic style on the webpage under analysis avoids opaque phrasing and thus the overall impression is one of clarity, objectivity and straightforwardness in the transmission of the message. There is no intention to obscure information or be evasive on purpose, which is proven by the rare use of modal verbs or conditional constructions. Passives are used primarily when there is news about unfortunate events happening to individuals. There is an interesting way of constructing gender when it comes to power, as women are either victims or, if empowered, this is the result of having capitalized on attributes of their gender, such as temptress attractiveness, in some dishonest manner. In this respect, we may further observe that women are considered through a patriarchal lens, which frames their assessment based on aspects related to traditional roles and assumptions, such as luring

attractiveness, the need to be proper in conservative views, and being weaker than men. The implied presence of these assumptions proves that the journalists believe that they are addressing a culture that is still conservative and male-controlled.

As we have seen, the state is seen as the one holding power through its institutions, bodies and personalities, which appear as decision-making factors. They do not always act in the best interests of the citizens, professionally or transparently, however, being depicted as more at fault than performing well. All the headlines show that most actors described in them are overridden by conflict, in many of its forms. Linguistically and stylistically, the presence of oppositions and binary phrasing mirrors the concept of conflict. The main stance is one of accusation and blaming of the authorities for the situation the country is in – hence, the use of irony and heavily-connoted terms of “carnival”, “4 musketeers” etc. One could detect a recourse to moral framing, out of which the empowered state actors appear as blameworthy, and their holding of power is questioned and implied to be problematic, undeserved or even illegitimate. Failure of the state to ensure a corruption-free, professional, orderly and safe climate for its citizens raises the issue of contestable and contested authority, which is visible throughout the homepage.

There is a predisposition to dramatize and enhance the gravity of the events depicted, visible in the terms used, which tend to be impactful and radical, pointing to marked, overt and preponderantly theatrical, dramatic reactions. Emotionality plays an important role, the news raising a wide array of emotional reactions in the readers, as if a target to cover as many of them were set, these ranging from outrage, revolt, anger, frustration, to fear, as well as compassion or pity. We could say that negative emotions are triggered for the most part, the positive ones being almost absent. This depends on the selection performed by the journalists as well, but how the citizens’ lives are impacted negatively by the measures and decisions made by the officials takes primacy and is of the highest interest, which is only natural against a background of crisis. Hence, the negativity arises not necessarily from the way the news items are presented, but from what is actually going on in the public sphere at a time of generalized crisis.

As a result of the analysis, the idea that power is assigned not only to entities depicted in the news, but also others, outside the context of the news discourse, arises. Namely, the readers are empowered through various means, one being the way in which they become possessors of knowledge, as well as privy on secret information. The journalists are also empowered as sources of information, professionals and experts, as mediators of knowledge, decoders providing a hermeneutic of facts, as well as vigilantes, potential exposers of irregularities. They acquire brand image capital while siding with the citizens and working to serve their interests – i.e. those of the many, among whom they include themselves – appearing as professional, dedicated and even heroic, at an extreme. Going back to the idea of power, they become the ones imparting legitimacy through the uncovering of uglier truths, thus negotiating power and dealing with it in a dynamic way,

taking some of it away from the authorities and giving it back to the public through knowledge. A noteworthy aspect is that information online reaches far more numerous audiences than television news broadcasts, as it can be consulted anywhere at any given moment, free from time restrictions. We may conclude that power plays performed through journalism are far more complex than at the level of the actual content on the website homepage, taking place on a much wider arena and at plural levels, operating changes in society in mentalities and seeing its effects in activism and, further, in how power gets (re)distributed concretely.

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POSSIBILITIES OF ANALYSING THE ECONOMIC AND FINANCIAL PERFORMANCE OF ECONOMIC ENTITIES THROUGH THE IMPLEMENTATION OF ACCOUNTING INFORMATION SYSTEMS

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Abstract

The accelerated evolution of digitisation and information technologies in recent years, together with growing competition in the business environment, have led to a profound transformation of the activities carried out within economic entities. The fundamental purpose of this study is to investigate in depth the influence that accounting information systems, especially ERP systems, have on the organisational performance of economic entities. This influence is analysed from the perspective of reducing operational costs, optimising the decision-making process and improving the efficiency of decision-making by management. The central objective of this research is to investigate how ERP information systems influence organisational performance, as well as to assess the perception of employees within economic entities on the use of these IT solutions in their daily professional activity.

Keywords: accounting information systems, economic and financial performance, ERP, economic entity, decision-making process, efficiency

JEL Classification: M41

1. Introduction

Performance is one of the most commonly used terms in everyday life to reflect progress. If we refer strictly to the measurement of results achieved by an individual, a member of the entity, this will be called individual performance. However, when referring to the

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concept of economic performance at the organisational level, performance management is one of the responsibilities of the entity's management, and this is exercised through the implementation of measures and actions aimed at increasing performance.

With this study, we seek to demonstrate that the use of modern accounting information systems has a positive impact on economic entities, for the purpose of achieving above-average results, namely high and very high performance. We have addressed this topic because we believe that a large number of domestic economic entities do not pay sufficient attention to this segment, refusing to invest the necessary resources to implement modern IT solutions that would simplify work processes and, implicitly, increase performance.

The rapid evolution of digitalisation and IT technologies in recent years, together with increased competition in the business environment, have led to a profound transformation of the activities carried out within economic entities. In this context, traditional processes based on manual labour and excessive use of paper for information transmission have been replaced by efficient digital solutions. ERP-type information systems, implemented by an increasing number of economic entities, contribute to the rigorous monitoring and planning of daily activities, providing managers with a clear, complete and accurate picture of the organisational situation.

These IT systems facilitate optimised resource management, minimising waste and reducing the risks associated with their inefficient use. As a result, ERP systems have become basic tools for carrying out the current activities of economic entities, supporting the flow of information and contributing to the decision-making process.

The need to implement these systems stems mainly from the increasing volume of data and documents that must be processed within a limited time frame, in correlation with the entity's development objectives. An additional reason for adopting these solutions is the *"possibility of meeting the organisation's objectives in real time"* [1], given that the information generated through these systems is complete, accurate and delivered promptly. The modular structure of ERP systems, together with their ability to integrate data into a single database, significantly streamlines the process of data sharing between the entity's different departments. Thus, they provide *"an accurate and complete picture of the entity's situation"* [1]. Each module is designed to include functionalities specific to the needs of each department, thus contributing to ensuring transparency and consistency of data at the organisational level.

The main role of these systems is to *"share and transfer data and information"* [2], both within the entity and in its external relations. In addition, ERP systems support the process of optimising and automating business operations and provide a solid basis for strategic decision-making by management.

2. Literature review

In recent decades, technological progress has led to the accelerated and refined development of information systems, contributing significantly to the optimisation of how entities operate. These systems aim not only to streamline internal activities but also to increase competitiveness in relation to other entities in the same sector. In this context, this study aims to investigate in depth the influence of integrated ERP-type information systems, both on the overall performance of the entity and on how they influence the work of accounting professionals.

Numerous specialist studies have outlined various perspectives on the definition of accounting information systems and highlighted the significant impact that the implementation of ERP solutions can have on organisational performance.

Accounting information systems are often described as platforms for collecting, storing and processing financial and accounting data, information that is subsequently used by decision-makers within organisations. *Onete & Dina* emphasise that these systems play a fundamental role in business administration and management, decisively influencing the economic development of entities, which makes them an indispensable element of long-term success.

According to *Bagranoff et al.*, accounting information systems are defined as a “*collection of data and procedures*” [4], designed to provide relevant and accurate information to interested users. An important advantage of ERP systems is their ability to centralise information in a single database, thus enabling the storage and sharing of basic data between different departments and organisational functions.

Through these integration mechanisms, the entity's management, as well as external parties, can access the information necessary for planning, control and decision-making processes in a timely manner. Thus, ERP systems serve to bring together a *multitude of business processes and activities*, and the accounting information they generate provides managerial support in making the most effective strategic decisions. From *Alnajjar's* perspective, accounting data processed through ERP is a “*crucial ingredient*” [5] in organisational decision-making, whether managerial or financial. That is why the processing of this information requires a high degree of rigour, thus ensuring transparency and clarity in the reports generated, as illustrated in Figure 1.



1. Data flow and ERP systems

Source: authors' processing

Any modern entity needs to invest in complex IT solutions, such as ERP systems, in order to strengthen its operational efficiency, reduce waste of resources and unnecessary consumption of electricity, and increase overall labour productivity. These integrated IT systems contribute significantly to the optimisation of internal processes by automating workflows and improving decision-making capabilities.

In a comprehensive study, *Ahmad and Al-Shbiel* highlighted that the literature supports the effectiveness of ERP systems in increasing organisational performance, which can only be achieved if entities are willing to accept and manage the environmental changes that may arise as a result of implementing these technologies [6]. In this regard, *Esmeray* emphasises that ERP systems play an essential role in supporting decision-making and internal control processes, becoming an indispensable tool for effective governance [7].

In terms of organisational performance, *Gruian* defines it as an entity's ability to access, allocate and use resources in an optimal way so as to obtain a level of remuneration

sufficient to cover the risk assumed and to maintain interest in the context of long-term sustainable development.

However, although organisational performance can be assessed using a variety of indicators, the literature does not provide clear guidance on selecting the most appropriate IT system to ensure performance improvement.

Sousa et al. also used a series of qualitative indicators – including productivity, customer satisfaction and the degree to which their needs are met – to comprehensively assess organisational performance [8]. On the other hand, financial performance is measured using specific indicators calculated on the basis of data generated and managed using ERP systems.

3. Research methodology

In order to achieve the established research objective, a mixed methodological approach was used, combining quantitative and qualitative methods, as well as theoretical analysis of the specialised literature.

The research methods used were summarised as follows:

Theoretical research, focused on exploring relevant concepts in the literature, with the aim of outlining a solid conceptual framework for the in-depth analysis of the topic under investigation;

Quantitative research, structured around two components:

Bibliometric analysis, designed to highlight the benefits of implementing ERP systems in improving organisational performance, by selecting and examining scientific papers indexed in established databases, such as Web of Science and Scopus;

Analysis of financial data from the financial statements of selected entities that have implemented ERP systems, comparing their performance before and after implementation (over a period of three years) by calculating relevant financial indicators in order to highlight the impact of ERP systems on organisational performance.

4. Proposals for innovative solutions regarding the integration of modern information technology components into financial-accounting information systems

The concept of performance has been defined in the explanatory dictionary of the Romanian language as “an outstanding result achieved in a particular field of activity”. *Niculescu and Lavalette* define performance as “a state of competitiveness of an economic entity, achieved through a level of productivity and efficiency that ensures its sustainable presence on the market” [9]. *Albu, C. N. and Albu, N.* define performance as the ability of an entity “to progress through constant efforts” [10], which can also be defined by three other concepts: effectiveness, efficiency and value.

Gruian defines the performance of an entity as “the ability to access resources, allocate them and use them optimally in order to obtain sufficient remuneration to cover the risk assumed and justify the interest, on the path to sustainable future development” [11].

However, it is considered that each area within the entity contains specific values that can be monitored, such as: in the marketing department, entity statistics are tracked; in the sales department, new opportunities and potential customers are monitored; and managers

analyse financial values. Values are quantified through performance indicators. Performance indicators are defined in M.P.F. Order No. 285/2009 as the unit of measurement that examines and indicates the performance strategy, providing clear and accurate information about the entity's situation.

Higgins and Hack (2004) identified three categories of performance indicators [12]:

- financial and non-financial indicators;
- reactive indicators (based on past results) and proactive indicators (based on future estimates);
- internal and external indicators for the purpose of analysing the internal and external performance of the entity.

The main characteristics of a performance indicator that *Bradford* (2015) identified in his work are [13]:

- they are based on corporate standards and valid data,
- they are easy to understand by stakeholders (what they represent, how they are measured and how the indicators are calculated),
- they are relevant to the entity,
- it leads to positive actions.

There are five reasons why performance measurement is necessary, as shown in Figure 2:

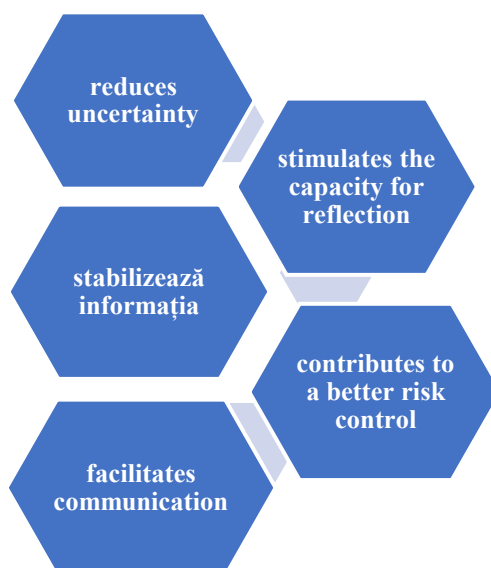


Figure 2. Reasons for measuring performance by an organisation

(Source: adapted from information in M.P.F. Order No. 285/2009)

Ormenișan considers that performance indicators are necessary for control, self-assessment and consistent improvement so that possible errors that the entity may face can be identified [14]. The entity's management has the role of detecting deviations from the desired performance, but also of planning and achieving the objectives set for the entity. For the

short-, medium- and long-term development of the entity, performance measurement systems must comply with a minimum set of 15 principles, as presented in Figure 3.



Figure 3. The 15 principles that must be followed for organisational performance measurement systems

Source: author's processing

According to *Kanji and Moura [15]*, performance measurement can fulfil the following roles:

- verifying the entity's progress at a given time in order to meet the set objectives;
- presenting managers with information relevant to ensuring the entity's success and identifying areas or aspects that require further improvement;
- enabling the development of effective and efficient strategies necessary for the entity's development.

Performance measurement has three meanings according to *Neely et al. [16]*, which are presented in Figure 4:

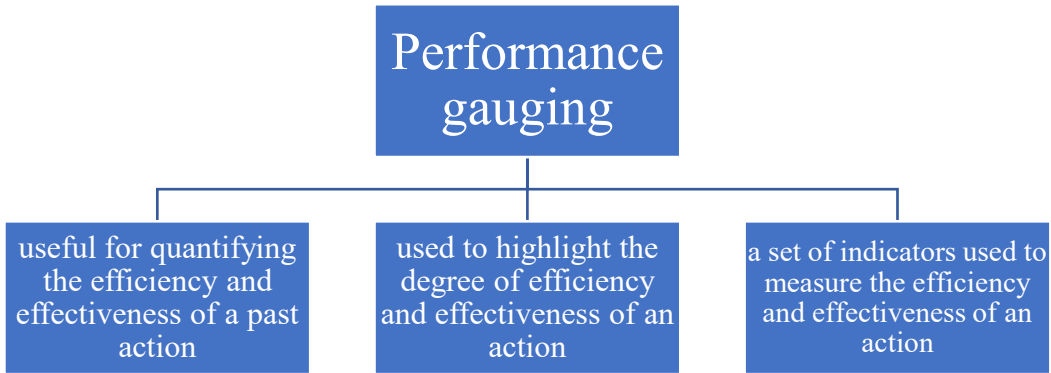


Figure 4. The three meanings of performance measurement

Source: authors' processing

In other words, *Lohman* characterises the concept of performance measurement through five criteria presented in Figure 5, such that the combination of the five elements will lead to beneficial results for the entity [17].

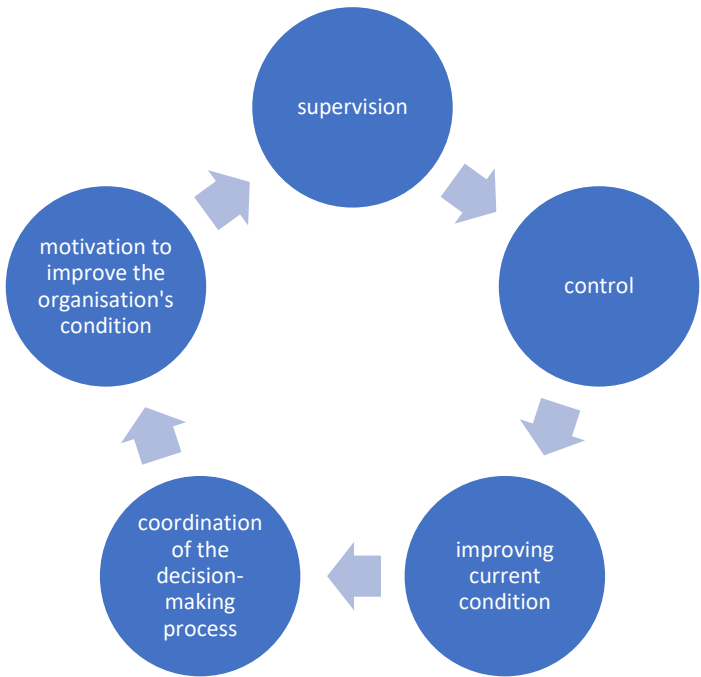


Figure 5. Characterisation of the concept of performance measurement

Source: authors' processing

In order to analyse the performance of an entity, the following aspects should be identified according to *Bratian* [18]:

- correlating the entity's performance indicators: the entity's strategies, objectives and budget;
- identifying the categories of indicators that are critical for an entity in order to identify its situation - indicators that reflect the entity's vision, mission, values and objectives;
- identifying financial and non-financial indicators that reflect the entity's situation as accurately as possible;
- aligning organisational levels.

Thus, in order to measure performance indicators, it is necessary to centralise all data/information within the entity using ERP-type information systems. ERP systems are designed to integrate information from within and outside the entity and to provide real-time processed information to employees and business partners. ERP systems are information systems that enable entities to identify, collect, integrate and structure all business processes in different departments of an entity, providing data to employees in the shortest possible time.

Saeed et al. state that ERP systems allow entities to automate a number of functions related to technology, services and human resources [19]. The main functionality of ERP systems is that they allow the creation of a permanent data backup, coordinating the flow of information in the database.

Entities in the economic environment decide to implement IT systems because they expect to generate financial benefits in the shortest possible time and maximise them using their own management techniques.

The implementation of ERP systems promotes operational efficiency and the transformation of all processes within an entity, offering numerous benefits. In the study conducted by *Balic et al.*, the quality offered by ERP systems was analysed from the perspective of three dimensions [20]:

- ERP information quality - understood as the way in which data meets the needs and requirements of users;
- ERP system quality – reflected in the system's capacity and the quality of information processing to meet technical requirements;
- ERP service quality - relating to customers' normative expectations and the perceived performance of the services provided by ERP systems.

Thus, the three dimensions have an impact on financial and non-financial performance indicators.

Financial performance indicators can be classified into two categories:

- rates of return – on investments, sales, inventory turnover;
- cost-related indicators savings.

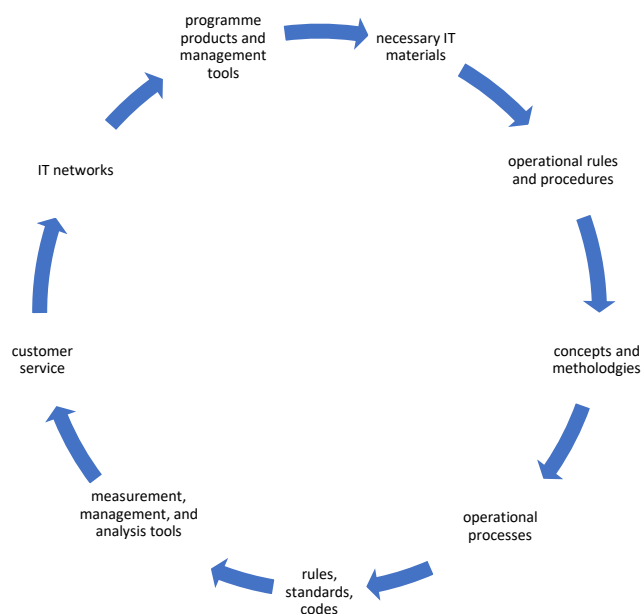
The results show that the implementation of ERP systems influences these indicators in the long term and that the impact of ERP system implementation is rarely visible in the short term. Non-financial indicators come from improvements in processes, workflow and access to information as a result of data processing using ERP systems.

5. Analysis of factors affecting organisational performance and the positive impact of implementing accounting information systems

The role of ERP systems is to integrate all information into a database from all departments of an entity, while facilitating the elimination of boundaries between departments and functional delimitations.

Given the upward trend in the modernisation of equipment and programmes used by entities as a result of technological progress, many of them decide to invest in the implementation of ERP systems. The main goal is to increase efficiency and flexibility, reduce maintenance costs, minimise risks, and integrate and process data in a single database shared by all departments of an entity. However, in the process of implementing these ERP systems, the risks to which the entity may be exposed in the process of transferring data from the database of the previous application to the database of the new application should be taken into account. Thus, ERP systems have the role of determining changes in the entity's strategy and vision. It should be noted that ERP systems have the role of eliminating problems that arise in resource management and clarifying the issues presented in Figure 6:

Figure 6. Problems arising in the management of an entity's resources



Source: authors' processing

Once this system has been implemented, it brings about changes both in the way activities are carried out and in the organisation. According to *Gargeya and Brady*, an ERP system is a system that allows the entity to have greater visibility of the information stored in the database and “to have better control over operations” [21].

Authors *Gargeya and Brady* have identified the main tangible and intangible benefits of the ERP system, which are presented in Table 1.

Table 1. Benefits of implementing ERP systems

Tangible benefits	Intangible benefits
• Reduction in material storage; • Reduction in personnel (i.e. reduction in salary and other salary-related expenses); • Improved productivity; • Improved management process; • Improved financial cycle; • Reducing utility costs; • Improving cash management; • Increasing revenue/profit; • Reducing time spent on equipment maintenance.	• Information visibility; • New/improved processes; • Integration and standardisation of information; • Flexibility; • Increased business performance.

Source: Gargeya and Brady, 2005

At the same time, it has been observed that entities that have implemented ERP systems can more easily achieve the following objectives:

- Integration of numerical data useful for the presentation of financial information;
- Centralised data control, eliminating data falsification;
- Integration of business processes;
- Standardisation of business operations;
- Accurate data analysis;
- Evaluation of programmes or decision-making processes.

In addition, ERP systems also bring about cultural and professional changes, as the technology stimulates employee creativity by organising the volume of information into a network, with all information collected from departments being stored in a single database.

The role of employees changes as a result of the implementation of this system, as they spend more time analysing different data and less time processing documents. However, professional evaluation criteria will also change, with more emphasis on skills and less on performance.

Other benefits of implementing ERP systems identified on the Wikiejemplos.com website are: automation of processes carried out within the entity in order to constantly improve the efficiency of daily operations, a higher degree of control and traceability that allows close monitoring of all processes within the entity, improvement of the decision-making process

as a result of the quality of information processed with ERP systems and the stability of information because all information is stored in a single database.

Soja (2016) [22] identified the main success factors in ERP implementation, divided into two sections, presented in Table 2:

Table 2. Success factors in ERP system implementation

Working environment	Methodological
• Description of the entity's activity; • High productivity; • Entity's willingness to change.	• Use of the embedded approach to implementation.

Source: authors' processing

According to Yang and Su (2009), the main benefits of ERP systems that offer improvements in an entity's performance have been identified, as presented in Table 2.3[23]:

Table 3. Main benefits of ERP systems and their impact on performance from different perspectives

ERP benefits	Performance
<u>Operational benefits</u> • Operational: automation of the functional process; • IT infrastructure: reduction of equipment maintenance costs.	• Outlook on the internal business process - Improving of inventory management; - Improving business process; - Improving information support. • Perspective on the external business process - Improving the business process with the external environment; - Improving customer relations • Customer service perspective - Improving customer satisfaction; - Improving flexibility. • Cost management
<u>Tactical benefits</u> • Managerial: efficient planning of data, production, inventory and physical resources.	
<u>Strategic benefits</u> • Strategic: possibility and support offered by systems for the development of the entity; • Organisational: development of the learning process within the entity and increased employee morale.	

Source: Yang and Su, 2009

In order to quantify the main benefits of implementing ERP systems, a *bibliometric analysis* was performed on the main articles rated by Web of Science that deal with this topic. The sample of articles was selected on 20 November 2022 based on the following keywords:

ERP, performance and benefits, resulting in a sample of 573 articles. The main Web of Science categories in which the articles were published are: Management, Neuroscience, Business, Computer Science Information Systems, Environmental Studies.

The journals that published articles on the benefits of ERP systems on organisational performance are presented in Figure 7:

☐ 6.3 Management	277	☐ 4.61 Artificial Intelligence & Machine Learning	4	☐ 1.203 Neuromuscular Disorders	1
☐ 1.7 Neuroscanning	131	☐ 1.172 Sports Science	3	☐ 1.208 Vasculitis & Autoimmune Disorders	1
☐ 4.84 Supply Chain & Logistics	14	☐ 4.47 Software Engineering	3	☐ 1.68 Lipids	1
☐ 6.115 Sustainability Science	11	☐ 4.48 Knowledge Engineering & Representation	3	☐ 2.114 Organic Semiconductors	1
☐ 1.5 Neuroscience	10	☐ 6.11 Education & Educational Research	3	☐ 3.16 Phytochemicals	1
☐ 1.136 Autism & Development Disorders	7	☐ 6.317 Risk Assessment	3	☐ 3.40 Forestry	1
☐ 1.21 Psychiatry	7	☐ 1.137 Sleep Science & Circadian Systems	2	☐ 4.13 Telecommunications	1
☐ 4.387 Security Systems	7	☐ 4.237 Safety & Maintenance	2	☐ 4.58 Wireless Technology	1
☐ 4.224 Design & Manufacturing	7	☐ 4.46 Distributed & Real Time Computing	2	☐ 6.185 Communication	1
☐ 1.52 Neurodegenerative Diseases	6	☐ 5.98 Geometrical Optics	2	☐ 6.223 Hospitality, Leisure, Sport & Tourism	1
☐ 6.10 Economics	6	☐ 6.263 Agricultural Policy	2	☐ 6.24 Psychiatry & Psychology	1
☐ 1.82 Gait & Posture	5	☐ 6.294 Operations Research & Management Science	2	☐ 6.27 Political Science	1
☐ 1.150 Hearing Loss	4	☐ 6.69 Language & Linguistics	2	☐ 6.73 Social Psychology	1
☐ 1.44 Nutrition & Dietetics	4	☐ 1.151 Pancreas & Gall Bladder Disorders	1	☐ 7.63 Mechanics	1
☐ 10.240 Music	4	☐ 1.199 Lung Cancer	1		

Figure 7. Journals that presented the benefits of ERP systems on the performance of entities and the years of publication of these journals

☐ 2023	1	☐ 2014	41	☐ 2005	8
☐ 2022	34	☐ 2013	35	☐ 2004	3
☐ 2021	33	☐ 2012	35	☐ 2003	7
☐ 2020	32	☐ 2011	26	☐ 2002	8
☐ 2019	30	☐ 2010	22	☐ 2001	3
☐ 2018	46	☐ 2009	23	☐ 2000	3
☐ 2017	46	☐ 2008	18	☐ 1999	3
☐ 2016	38	☐ 2007	17	☐ 1994	1
☐ 2015	46	☐ 2006	13	☐ 1992	1

Source: Web Of Science Platform, 2022

The reason why the number of articles published on the topic of ERP systems has gradually increased since 2012 is due to the rapid growth in the rate of ERP system implementation among entities.

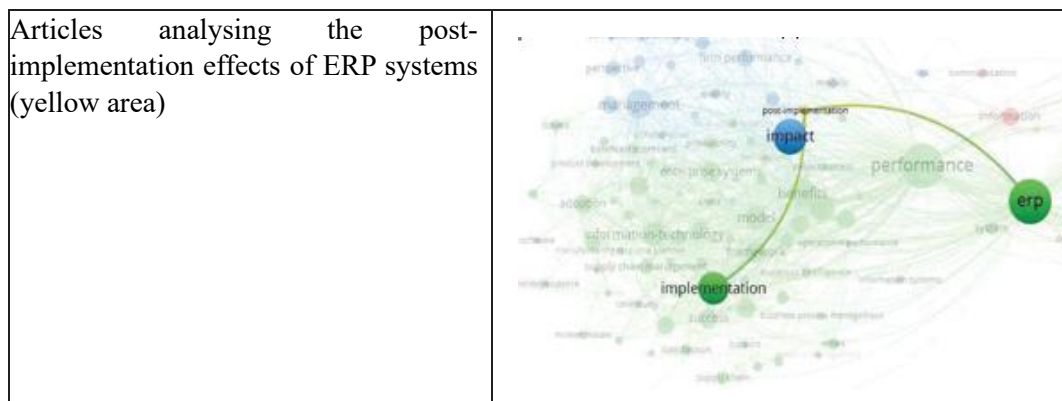
The evolution of ERP system implementation rates is shown in Figure 8.

Figure 8. Evolution of the implementation rate of ERP systems

Following the analysis, the following four clusters were identified based on the keywords identified in the 573 articles, presented in Table 4:

Table 4. Analysis of the 4 pairs of clusters that define the benefits offered by ERP systems

Articles in the medical field (red area), containing words such as: attention, cognitive control, memory activity, brain activity, recognition and others.	
Articles in the field of ERP system implementation (green area, with implications in the blue area), containing words such as: information technology, conceptual framework, success, meeting requirements, operational performance, business intelligence, productivity.	
Articles analysing the benefits of ERP system implementation (blue area), containing words such as: impact, strategy, management, perspective, financial performance, advantages, sustainable development.	



Source: authors' processing

Based on the information presented in Table 4, it can be stated that the largest proportion of articles focus on the benefits of implementing ERP systems, as many entities are interested in the main functions of ERP systems and the possibility they offer to streamline their activities.

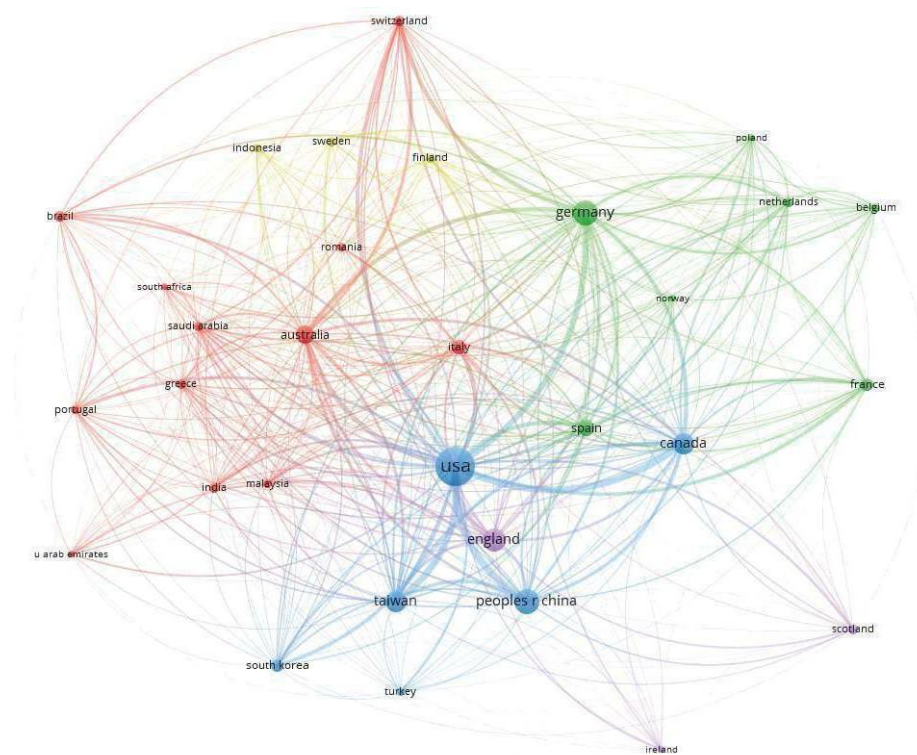


Figure 10. Bibliometric analysis of the main countries where articles were written about the benefits offered by ERP systems for improving performance

Source: authors' processing

According to Figure 10, most articles were written in the USA, Canada, China, Germany, Taiwan and Australia, as these are the most developed countries in terms of technology. Based on the specialised literature, internal and external factors that could disrupt the entity's performance were identified, these being represented by:

- Internal factors: organisational culture, communication within the entity, quality of decisions made by its management.
- External factors: restrictions imposed by the state, sudden legislative changes, market fluctuations.

The first internal factor is the entity's culture, defined as a complex model of beliefs and aspirations shared by its members, including employee behaviour, rituals and ceremonies. If misunderstandings arise between members or employees of the entity, the flow of information will be disrupted and could affect its entire activity. Communication is another important factor for performance, as a correct and continuous flow of information between managers and team members, with the aim of defining expectations and sharing information about the entity's mission, values and objectives, is essential. The third internal factor is the quality of the decisions taken by the entity's management. The more rigorously data is processed using IT systems, the more accurate and clearer the data used by managers in the decision-making process will be, adding value to the entity's activities. This is also due to the fact that all data is centralised and stored, after processing, in a single database, which makes data analysis much easier for managers.

Analysing the first two external factors relating to state restrictions and legislative changes can have a major impact on the performance of both employees and the entity. The areas most vulnerable to legislative changes that can influence the entity's performance are shown in Figure 11:



Figure 11. Areas vulnerable to legislative changes

Source: authors' processing

Legislative changes can negatively influence the entire activity of the entity, generating possible decentralisations of the model or information flow within it. Laws are regulations that serve to constrain, guide or protect entities, with the aim of resolving various conflicts that may arise at the organisational level.

These legislative changes are also influenced by market fluctuations (changing consumer preferences, natural events, etc.). However, the purpose of ERP systems is to provide or report information as accurately and transparently as possible.

The main features of these systems are shown in Figure 12.

Integration	Standardisation	Centralising organisation data	Automating daily tasks
• linking all functions/activities of the organisation in a database	• organisation rules are based on good practices	• data is stored in a single database	• enables streamlining of activities

Figure 12. Characteristics of ERP systems

Source: author's processing

As can be seen in Figure 12, the main key features of ERP systems found in the literature are:

- Integration;
- Standardisation;
- Data centralisation;
- Automation of daily tasks.

6. Study of performance indicators and the influence accounting information systems have on them

The concept of an entity's performance has been defined from various perspectives. The main definition of performance refers to profit maximisation, but also to the entity's ability to cope with competition. Performance can also be viewed in terms of productivity or the objectives set by the entity. Performance analysis is based on two key aspects: performance indicators and the performance measurement system. Performance indicators reflect the degree of efficiency and effectiveness of actions or activities carried out by an entity in a given period, but may also vary depending on its size.

The main categories of performance indicators that can be influenced by the implementation of ERP systems are:

- Accuracy of the invoicing process and information flow;
- Fixed assets;
- Operating expenses;
- Net profit;
- Break-even point;

- Earnings before interest, taxes, depreciation and amortisation – EBITDA;
- Asset turnover ratio, asset turnover period;
- Current/intermediate liquidity;
- Solvency ratios;
- Rates of return: on total assets – ROA, on equity – ROE, on resources consumed – RRC.

The reason why these indicators are directly influenced by the implementation of an ERP system is that the acquisition and integration of these systems involves a significant financial effort, which affects both the liabilities and assets in the balance sheet and the expenses (equipment maintenance, training programmes) in the profit and loss account. The entity's performance can only be accurately assessed after the successful implementation of an ERP system, as shown in Table 5.

Table 5. Effects of ERP system implementation

ERP systems environment	• Correct selection of the ERP system according to the entity's requirements and field of activity; • System analysis and testing; • Technological infrastructure; • System quality; • Support provided by the supplier; • Presence of consultants to provide information when uncertainties or problems arise in using the ERP system;	Results of the ERP system implementation project	Resulting business processes: • Operational efficiency; • Operational effectiveness; • Operational flexibility;
Adoption of ERP systems within the entity	• Presence of training programmes; • System development/customisation by the user; • Ongoing support of the management team; • Clear and well-defined objectives; • Re-engineering of certain processes.		

Source: authors' processing

In order to quantify how performance is influenced by the implementation of ERP systems in entities, a *bibliometric analysis* was carried out on the main articles indexed in Web of Science that deal with this subject. The sample of articles was selected on 20 November

2022, based on the following keywords: ERP, performance and implementation, thus obtaining a sample of 1006 articles.

The main Web of Science categories in which these articles were published are: Management, Computer Science Information Systems, Business, Operations Research Management Science and Information Science Library. The selected articles appeared in journals between 1997 and 2023.

Using the VOSviewer application, Figure 13 was constructed, illustrating the main keywords found in articles associated with ERP systems, thus obtaining nine clusters, highlighted as follows:

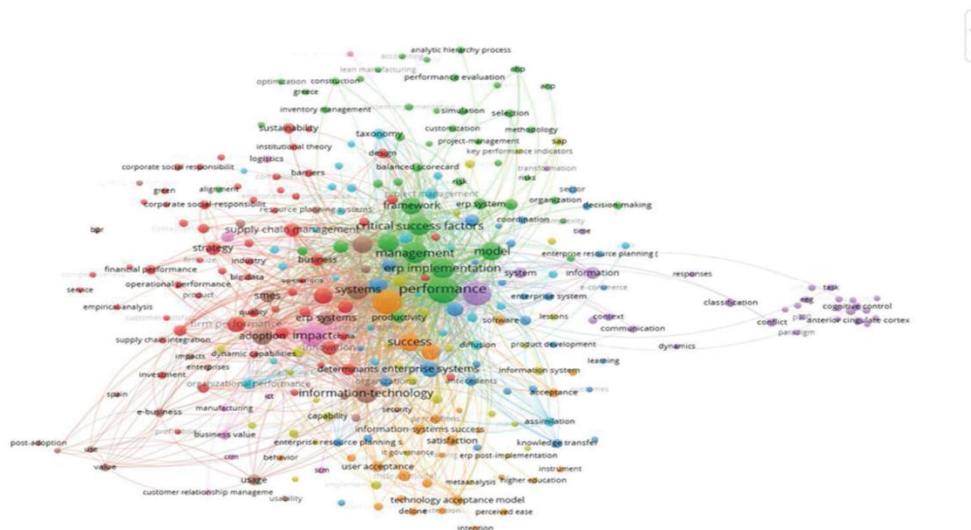


Figure 13. Bibliometric analysis of how the implementation performance of an ERP solution is influenced - Co-occurrence & Keywords option

Source: authors' processing

According to Figure 13, the nine clusters identified refer to the following aspects:

- The first group refers to new technologies - Big Data, Business Intelligence, Industry 4.0, but also to strategy and sustainable development;
- The second group refers to analysis, data processing, and the benefits offered by the implementation of ERP systems (improved decision-making, ERP system maintenance, productivity, organisation, performance, simulation, security of processed data);
- The third group includes data on the flexibility and support offered by ERP systems, as well as the development of these systems;
- The fourth group details the processing environment, performance indicators, success and risk factors in the implementation of ERP systems;
- The fifth group defines human perception and behaviour in the use of these systems;
- The sixth group defines the factors that influence the entity's performance, resource management, culture and the problems it may face;

- The seventh group presents the satisfaction of ERP system users' requirements regarding the activity carried out in entities;
- The eighth group presents the post-implementation effects of ERP systems, the quality of management decisions, and how data is saved on the server - Cloud;
- The ninth group defines logistics, CRM and supply chain management issues.

Analysing the countries of origin of the authors who have written about this concept, we find that the most recent articles were written in countries such as Indonesia, Russia, the United Arab Emirates and India, followed by articles written by authors from France, Romania, Turkey, Spain, Portugal, Germany and Sweden (2016–2018). The oldest articles come from countries such as the USA, Taiwan, and the Netherlands (before 2012) (Figure 14).

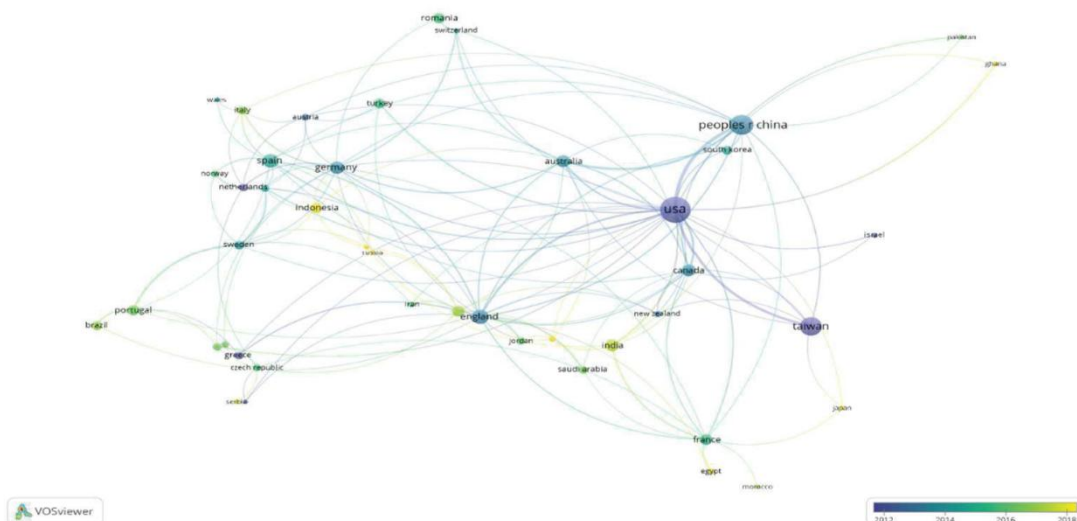


Figure 14. Bibliometric analysis of how the implementation performance of an ERP solution is influenced – Co-authorship & Countries option

Source: authors' processing

ERP systems can bring financial benefits following their implementation. Firstly, by reducing resource consumption, which results in lower resource procurement costs, and secondly, through sustainable development, which makes it easier to obtain financial benefits from the bank as a result of the implementation of the sustainable development project. In this context, several financial performance indicators affected by the implementation of ERP systems will be analysed, with a few key aspects defining these indicators being presented first in Table 6.

Table 6. Financial indicators used in the research study

Indicators	Formula	Brief description
Current liquidity ratio	$\frac{\text{Current assets}}{\text{Short-term liabilities}}$	Liquidity indicators reflect the organisation's ability to pay short-term obligations as they fall due, based on current assets represented by inventories, receivables and investments
Intermediate liquidity ratio	$\frac{\text{Current assets} + \text{Inventories}}{\text{Short-term liabilities}}$	
Cash liquidity ratio	$\frac{\text{Cash and cash equivalents} + \text{Short-term liabilities}}{\text{Current liabilities}}$	
Overall solvency ratio	$\frac{\text{Total Assets}}{\text{Total Liabilities}}$	Solvency indicators provide information about the organisation's ability to cover its total liabilities
Equity solvency ratio	$\frac{\text{Equity}}{\text{Equity} + \text{Bank loans}}$	
Return on assets (ROA)	$\frac{\text{Operating profit}}{\text{Operating assets}} \times 100$	Profitability indicators show whether the organisation is using all its resources to generate profit.
Return on equity (ROE)	$\frac{\text{Net profit}}{\text{Equity}} \times 100$	
Return on sales (ROS)	$\frac{\text{Profit}}{\text{Turnover}} \times 100$	
Return on Resources Consumed (RRC)	$\frac{\text{Operating profit}}{\text{Operating expenses}} \times 100$	Return rates provide information about the state of the organisation, reflecting the relationship between turnover and profit.
Asset turnover ratio	$\frac{\text{Turnover}}{\text{Average current assets}}$, where average current assets = $\frac{(\text{opening balance} + \text{closing balance})}{2}$	
Asset turnover period	$\frac{\text{Average current assets}}{\text{Turnover}} \times T$, where $T = 365$ days	

Source: authors' processing

The research study began with an analysis of creditworthiness indicators (liquidity and solvency indicators) and will continue with an analysis of profitability rates over a period of three consecutive years. The situation of the entities will be analysed before, during and after the implementation of the ERP systems.

Creditworthiness refers to the liquidity and solvency of the entity over a certain period of time. Liquidity can be understood as the entity's ability “to pay its short-term debts on the basis of short-term assets (current assets/current assets)”:

- Solvency can be understood as the entity's ability “to pay its total debts on the basis of its total assets”.

- The first ratio analysed in the proposed case study is the current liquidity ratio, which expresses the entity's ability “to cover short-term liabilities with current assets”.

Analysing the current liquidity ratio (Table 7) for the selected entities over a period of 3 years, significant changes in the entities' situation were observed: approximately 18.18% of the selected entities encountered difficulties in honouring their debts (marked in red), while 81.82% of entities achieved a current liquidity ratio above 1.5, providing assurance that those entities have the ability to discharge their short-term obligations (marked in green).

Table 7. Current liquidity ratio calculated over a period of 3 years

No.	Organisation	Year of ERP system implementation	Type of ERP system implemented	Situation before implementation	Situation in the year of implementation	Situation after implementation
1	Johnson & Johnson	2004	SAP ERP	1,710	1,962	2,485
2	Curtiss Wright	2015	Oracle ERP	2,747	3,365	3,313
3	SIFCO Industries	2015	MS DAX	2,762	2,158	1,144
4	Robert Bosch Power Tools GmbH	2016	SAP ERP	1,691	1,673	1,723
5	Avant	2016	Oracle Netsuite ERP	1,330	1,294	1,753
6	Tikkurila Sverige AB	2016	MS DAX	1,834	1,707	1,398
7	HP Inc.	2017	SAP ERP	0,982	0,996	0,851
8	Siemens Gamesa Renewable Energy S.A	2017	SAP ERP	1,279	N/A	N/A
9	Central Garden & Pet Company	2005	SAP ERP	2,704	3,059	3,062
10	Cooper Standard Automotive Inc	2008	SAP ERP	1,460	1,381	1,826
11	Sopharma	2017	MS DAX	1,409	1,289	1,224
12	Toyota	2018	SAP ERP	1,030	1,485	1,696
13	Engie	2018	SAP ERP	1,061	1,071	1,045
14	Titan Shops, a Division of CSU Fullerton Auxiliary Services Corporation	2018	Oracle Netsuite ERP	1,717	1,776	1,758
15	Chatham Financial	2018	Microsoft Dynamics GP	0,948	0,505	0,422
16	Tyson Foods, Inc.	2019	SAP ERP	1,131	1,300	1,862
17	Hewlett Packard Enterprise	2019	SAP ERP	1,004	0,790	0,884
18	Accenture	2019	SAP ERP	1,338	1,397	1,402
19	Colgate-Palmolive	2020	SAP ERP	1,035	0,985	N/A
20	Gartner	2010	MS DAX	0,621	0,766	0,766
21	Valora	2020	SAP ERP	1,028	1,027	N/A
22	Landbay	2020	Oracle Netsuite ERP	4,585	5,621	N/A

Source: adapted from Barna et al., 2021

The current liquidity ratio is influenced by elements that make up current assets and liabilities such as: inventories, trade receivables, short-term investments, cash and bank accounts, and short-term liabilities.

ABC Training Consulting believes that in order to become “liquid” and turn into cash, inventories must go through a process consisting of the following phases: sales, receivables, collections. The outcome of this process may depend on a number of quantitative and qualitative factors, such as: the degree of moral and physical wear and tear of inventories, the possibilities for capitalising on inventories, and the time taken to collect trade receivables.

The intermediate liquidity ratio in Table 8 indicates that more than 45% of the selected entities (marked in green) have a maximum capacity to cover payments that have reached maturity, while the other entities have problems in honouring payments when due. The optimal level of this ratio is between 0.8 and 1.

Table 8. Intermediate liquidity ratio calculated over a period of 3 years

No.	Organisation	Year of ERP implementation	Type of ERP system implemented	Situation before implementation	Situation in the year of implementation	Situation after implementation
1	Johnson & Johnson	2004	SAP ERP	1,443	1,693	2,171
2	Curtiss Wright	2015	Oracle ERP	2,067	2,693	2,332
3	SIFCO Industries	2015	MS DAX	1,774	1,315	0,583
4	Robert Bosch Power Tools GmbH	2016	SAP ERP	1,151	1,180	1,213
5	Avant	2016	Oracle Netsuite ERP	1,330	1,294	1,753
6	Tikkurila Sverige AB	2016	MS DAX	1,074	1,034	0,817
7	HP Inc.	2017	SAP ERP	0,744	0,738	0,610
8	Siemens Gamesa Renewable Energy S	2017	SAP ERP	0,964	N/A	N/A
9	Central Garden & Pet Company	2005	SAP ERP	2,612	2,904	2,893
10	Cooper Standard Automotive Inc	2008	SAP ERP	1,166	1,122	1,610
11	Sopharma	2017	MS DAX	0,862	0,740	0,679
12	Toyota	2018	SAP ERP	0,892	1,263	1,440
13	Engle	2018	SAP ERP	0,986	0,999	0,983
14	Titan Shops, a Division of CSU Fullerton Auxiliary Services Corporation	2018	Oracle Netsuite ERP	0,484	0,373	0,458
15	Chatham Financial	2018	Microsoft Dynamics GP	0,948	0,505	0,422
16	Tyson Foods, Inc	2019	SAP ERP	0,432	0,555	0,883
17	Hewlett Packard Enterprise	2019	SAP ERP	0,862	0,666	0,741
18	Accenture	2019	SAP ERP	1,338	1,397	1,402
19	Colgate-Palmolive	2020	SAP ERP	0,688	0,605	N/A
20	Gartner	2010	MS DAX	0,621	0,766	0,766
21	Valora	2020	SAP ERP	0,687	0,753	N/A
22	Landbay	2020	Oracle Netsuite ERP	4,585	5,621	N/A

Source: adapted from Barna et al., 2021

Analysing the overall solvency ratio (Table 8), it can be stated that most entities are solvent, exceeding the minimum threshold of 1.4, and are marked in green.

Table 9. Overall solvency ratio calculated over a period of 3 years

No.	Organisation	Year of ERP implementation	Type of ERP system implemented	Situation prior to implementation	Situation in the year of implementation	Situation after implementation
1	Johnson & Johnson	2004	SAP ERP	2,2559	2,4794	2,8791
2	Curtiss Wright	2015	Oracle ERP	1,7696	1,8678	2,0978
3	SIFCO Industries	2015	MS DAX	3,3164	1,8738	1,8614
4	Robert Bosch Power Tools GmbH	2016	SAP ERP	1,8035	1,7880	1,8473
5	Avant	2016	Oracle Netsuite ERP	2,0167	2,0390	29,6978
6	Tikkurila Sverige AB	2016	MS DAX	2,0456	2,0342	1,7232
7	HP Inc.	2017	SAP ERP	0,8818	0,9062	0,9819
8	Siemens Gamesa Renewable Energy S.A	2017	SAP ERP	1,4274	N/A	N/A
9	Central Garden & Pet Company	2005	SAP ERP	1,9863	2,0746	1,9019
10	Cooper Standard Automotive Inc	2008	SAP ERP	1,1418	1,0109	0,8500
11	Sopharma	2017	MS DAX	2,3349	2,0534	2,0129
12	Toyota	2018	SAP ERP	1,5949	2,0035	1,9491
13	Engle	2018	SAP ERP	1,3951	1,3631	1,3124
14	Titan Shops, a Division of CSU Fullerton Auxiliary Services Corporation	2018	Oracle Netsuite ERP	2,0765	2,2360	2,1690
15	Chatham Financial	2018	Microsoft Dynamics GP	2,3903	2,2770	2,1680
16	Tyson Foods, Inc	2019	SAP ERP	1,7860	1,7539	1,8147
17	Hewlett Packard Enterprise	2019	SAP ERP	1,6217	1,4949	1,4245
18	Accenture	2019	SAP ERP	1,7814	1,9910	1,8938
19	Colgate-Palmolive	2020	SAP ERP	1,0385	1,0743	N/A
20	Gartner	2010	MS DAX	1,1020	1,1703	1,1517
21	Valora	2020	SAP ERP	1,3544	1,3890	N/A
22	Landbay	2020	Oracle Netsuite ERP	8,3467	5,8881	N/A

Source: adapted from Barna et al., 2021

The optimal value of this indicator presented in Table 9 is above 1.4, in which case the entity can continue its activity without becoming insolvent. Analysing the solvency ratio, it can be seen that the entire sample of entities had no problems continuing their activity during the three years (Table 10).

Table 10. Equity solvency ratio calculated over a period of 3 years

No.	Organisation	Year of ERP implementation	Type of ERP system implemented	Situation prior to implementation	Situation in the year of implementation	Situation after implementation
1	Johnson & Johnson	2004	SAP ERP	1	1	1
2	Curtiss Wright	2015	Oracle ERP	1	1	1
3	SIFCO Industries	2015	MS DAX	1	1	1
4	Robert Bosch Power Tools GmbH	2016	SAP ERP	1	1	1
5	Avant	2016	Oracle Netsuite ERP	1	1	1
6	Tikkurila Sverige AB	2016	MS DAX	1	1	1
7	HP Inc.	2017	SAP ERP	1	1	1
8	Siemens Gamesa Renewable Energy S.A	2017	SAP ERP	0,8061	N/A	N/A
9	Central Garden & Pet Company	2005	SAP ERP	1	1	1
10	Cooper Standard Automotive Inc	2008	SAP ERP	1	1	1
11	Sopharma	2017	MS DAX	0,9499	0,9087	0,9252
12	Toyota	2018	SAP ERP	0,9721	1	1
13	Engie	2018	SAP ERP	0,6273	0,6077	0,5590
14	Titan Shops, a Division of CSU Fullerton Auxiliary Services Corporation	2018	Oracle Netsuite ERP	1	1	0,7299
15	Chatham Financial	2018	Microsoft Dynamics GP	1	1	1
16	Tyson Foods, Inc.	2019	SAP ERP	1	1	1
17	Hewlett Packard Enterprise	2019	SAP ERP	1	1	1
18	Accenture	2019	SAP ERP	1	1	1
19	Colgate-Palmolive	2020	SAP ERP	0,6822	0,8102	N/A
20	Gartner	2010	MS DAX	1	1	1
21	Valora	2020	SAP ERP	1	1	N/A
22	Landbay	2020	Oracle Netsuite ERP	1	1	N/A

Source: adapted from Barna et al., 2021

7. Conclusions

Information systems offer a multitude of benefits to both employees and entities, contributing significantly to the automation of redundant activities and the streamlining of internal processes. These systems are designed to support the achievement of the entity's strategic objectives by reducing operational costs and improving the management of repetitive and bureaucratic tasks.

The coherent integration of data within databases managed by an ERP system facilitates the decision-making process, allowing for the efficient allocation of resources and significantly reducing waste. By centralising information, ERP systems contribute to better interdepartmental coordination and a unified view of the entity's organisational performance.

One of the fundamental objectives of ERP systems is to stimulate employee productivity by providing them with modern work tools, while managers benefit from increased control over the decision-making process. IT platforms provide managers with quick and easy

access to essential information about the entity, thus contributing to more efficient and better-informed decision-making. Consequently, the implementation of ERP systems allows for the development of a clear and up-to-date perspective on the internal situation of the entity, increasing its ability to react and adapt to market dynamics. In this context, training programmes become essential to facilitate employee acceptance and use of the system, especially given that the implementation process is complex and can generate resistance to change. Following the implementation of these systems, the work of accounting professionals has undergone significant changes, with redundant tasks being replaced by value-added activities such as consulting and data analysis.

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TECHNOLOGICAL CHANGE IN HIGHER EDUCATION, CASE STUDY: THE ROLE OF DIGITAL TECHNOLOGY IN THE PROCESS OF TRANSFORMATION IN HIGHER EDUCATION IN REPUBLIC OF SERBIA

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Abstract

For centuries, civilizational development was achieved through the improvement of science and technology to improve the quality of life and acquire knowledge. At the end of the 20th century, significant global changes occurred in the world: social, economic, political, legal, technological, etc. Existing research shows that the present environment is characterized by technological changes and discoveries, but also by their rapid obsolescence. In the period of technological change, the digital transformation and the application of digital technology in higher education have attracted the attention of the scientific and professional public. These changes are becoming particularly significant for transition countries (e.g., Serbia), bearing in mind that the online platforms phenomenon for learning in the educational process expands the boundaries of traditional teaching and learning. The research deals with key issues related to the application of digital technologies in the transformation of higher education at universities (private and public) in the Republic of Serbia. The purpose of this paper is to consider how new tools can be applied to simplify the educational process and improve the learning process. The aim is to identify the potential for integrating social media through the student's perception of higher education in Serbia. Data were collected using a structured questionnaire based on the research questions: "How can higher education institutions integrate social media as an essential tool in the transformation of teaching and learning methods?" and "How and to what extent do students use digital technologies in the learning process?" The research involved students (300) from three faculties. Results indicated that students agree that social media should be used in the teaching process.

Keywords: technological change, digital technology, social media, higher education, Republic of Serbia

JEL Classification: I23

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1. Introduction

“We live in a world of change”

(“Engineering and Our Way of Life”, Augustus Braun Kinzel)

Today, man lives in a digital era characterized by the presence of accelerated scientific-technological and socio-economic development (Industry 4.0 and Society 5.0). According to this, new knowledge, advanced technologies, technology transfer and diffusion of knowledge, unrestricted global access to information, inclusion and circulation of qualified personnel in the global scientific-technological, economic, educational, and cultural integrative processes, have become imperative for development. Ideas, information, and knowledge are becoming the essence of the new economy and the basis for economic growth. Thus, the importance of factors such as the culture of work, entrepreneurship, and the “invention of invention” is discussed by Landes [1], analyzing the industrial revolution and the diffusion of technology. In addition, the author states that at the end of the twentieth century, with the scientific and technological revolution, the wealthiest country in the world had a higher per capita income than the poorest in the amount of 400:1, compared to the beginning of the fourth industrial revolution, when this ratio was only five times higher. Finally, considering that technological progress is an indicator of economic development, Landes analyzes the relationship that exists between technology and society, emphasizing that “... *disparities in wealth between certain countries are narrowing, but at the global level these disparities remain large*; “...*the import and export of jobs has a greatly different impact on the human ...*”; “*and that comparative advantages of countries can and do change.*”

Digital transformation (DT) is becoming a new paradigm in organizations that leads to reshaping the way they function, communicate, do business, and provide services in the environment. Thus, some authors see DT as an organizational change enabled by digital technologies that has the potential to modify every aspect of the organization. In addition, in recent years, DT has become a subject of interest to researchers and business managers as the concept is widely accepted. It is worth noting that in practice, numerous companies and individuals have supported DT and the application of digital technology with the possibility of substantial business changes (e.g., changes in products and organizational structures; optimization and automation of processes, etc.). Accordingly, DT is defined as “*the profound transformation of business operations and organizations, procedures, qualifications, and models, in a corporate strategy for optimum conversion of the changes and possibilities of a new tech variety and its incredibly rapid influence on the society*” [2], [3].

From a global perspective, the advancement of digital technology has led to significant transformations in communication and to unlimited access to information. Thus, Nikola Tesla predicted a new way of communication (cellphones) in 1926:

“When wireless is perfectly applied, the whole earth will be converted into a huge brain, which in fact it is, all things being particles of a real and rhythmic whole. We shall be able to communicate with one another instantly, irrespective of distance.”

The development of information and communication technologies (ICT) has influenced the evolution of existing and the emergence of new business and social communications. Namely, as two-way communication is established, new users are conquered, and their respect becomes the most significant determinant of successful communication (e.g., most people access information through mobile phones, tablets, and other devices).

Social media became a significantly important part and integral part of everyday life and one of the new channels of communication. The state of social media is best described by Siegel [4], a New York writer and critic of technology:

“The Internet has penetrated our lives more deeply than any other medium...[it] is now a permanent part of our civilization.” S druge strane, *“There are other social media platforms worthy of discussion and inclusion in education programs.”*

In this regard, they differ from mass media such as newspapers, television, and film, being relatively inexpensive, accessible, and providing the possibility to users to publish or access information. Communication with an increasing number of users is achieved through a service platform, whereby opening an account becomes a simple and free procedure. In contrast, the mass media require considerable resources to publish information.

Modern knowledge has confirmed the thesis that knowledge, learning, education, and social development are directly related categories. Knowledge manifested through new technologies, more efficient and quality processes, and a higher - quality workforce becomes the main driver of growth promotion. Education represents the main form of human capital formation. Higher education institutions (HEIs), public or private, have a mission to create, transmit, and use knowledge. They promote learning, teaching, research, and creativity in science, technology, the arts, and sports for community development and the well-being of society and its users. Accordingly, a survey of nearly 15,000 universities in about 1,500 regions in 78 countries from 1950 to 2010 showed that *“...increases in the number of universities are positively associated with future growth of GDP per capita. “...a 10% increase in a region's number of universities per capita is associated with 0.4% higher future GDP per capita in that region”*[5].

The modern era and way of life and habits are vastly different from those in which the current educational system was created. Considerable emphasis in the literature has been devoted to the technological changes that have occurred over recent decades in education. In this sense, the academic community has turned its attention to digital technologies and their integration into higher education institutions. Namely, digital technologies are becoming a tool for expanding the boundaries of traditional learning - conducting classes

with students, developing students' competences and skills (e.g. workforce for the modern labor market), improving educational methods (e.g. online learning platforms; combined learning models, etc.) and to increase the educational activities efficiency (e.g. supervision, control, management) to obtain simplification of the organization of the educational process [6].

By reviewing literature and practice, researchers have attempted to answer the questions: "What happens when social media is integrated into academic purposes?" and "How did social media, from a tool for social interaction, become part of educational methodologies and practices across the planet?"

In the age of social media and smartphones, universities and colleges have the opportunity to choose their users (students) with a new "online environment", as was done traditionally. Therefore, their usage becomes significant in the promotion of higher education institutions. Additionally, the integration of social media into higher education institutions has contributed to the advancement of digital literacy, increasing experience and learning outcomes, as well as the development of critical thinking skills. Otherwise, in practice, the main problem becomes adapting this tool to higher education and improving student satisfaction.

The Republic of Serbia, as a transition country, has actively engaged with the European Research and Education Area in order to create a knowledge-based society. General education, as well as digital education and technological change, are gaining significant importance in the transformation of the economy and civilization (e.g., the terms "digital economy", "digital market", "digital society", and "digital education" are increasingly present). In particular, numerous analyses have shown that the introduction of digital technologies into the educational process is necessary for the transition from traditional to modern forms of education. Moreover, the strategic goal of the Government of the Republic of Serbia has become the digitalization of education (e.g., introduction of informatics as a compulsory subject from the first grade of primary school; introduction of electronic services, e-books, and online classrooms; e-enrolment in primary and secondary schools; etc.). Furthermore, the strategic goal of the Government of the Republic of Serbia has become the process of digitalization of education (e.g., introduction of informatics as a compulsory subject from the first grade of primary school; introduction of electronic services, electronic books, and online classrooms; e-enrolment in primary and secondary schools, etc.).

In accordance with the state development strategies, by mid-2023, Serbia had introduced fast, secure internet access in 1.843 schools (which educate more than 730.000 students and employ over 100.000 teachers and professors). Over 1.000 facilities have ultra-fast optical internet speeds of 300 Mbps. In fact, considering that digitization is a long-term process and requires continuous effort and work, it is primarily due to the pervasive nature of significant inequality between rural and urban education institutions. At the same time, the

Unique Educational Number (UEN) was implemented as a key tool in education. In general, the UE number follows pupils or students through their entire schooling and serves to archive data from preschool to university level, thus avoiding various abuses - for example, students concurrently enrolling in academic programs while being funded by the state budget [7].

This paper aims to recognize the potential for integrating social media into higher education in Serbia, and the purpose is to consider the role and importance of new digital media tools to simplify the educational process and improve the learning process. In particular, the research is directed toward students' perception of social media use at three faculties during the 2024-2025 academic year in Serbia.

2. Literature Review

Theoretical Background

“We shall be able to witness and hear events... just as though we were present.”

(Tesla, N. on the technology, 1926)

Due to technological progress and development, human have changed their nature and thus satisfied their own desires and needs. At the beginning of the development of civilization, the concept of technology was related to the transformation of natural resources into simple tools, then to their further development and adaptation to the aspirations and environment. Accordingly, it was understood that the educational process can contribute to further progress, for example, by improving a person's creative, social, cultural, psychophysical, and ethical potentials. At the same time, further technological progress (Industry 4.0) has contributed to the application of digital technologies in education. It is important to emphasize that new forms of academic teaching, learning, and knowledge have been acquired outside of higher education institutions due to the phenomenon of information overload and knowledge in the digital sphere. The use of innovative media and technical infrastructure to reshape teaching and learning methods (e.g., individualization and flexibility; use of digital teaching and educational resources; distance learning; 'virtual mobility'; digital exams; adaptation of teaching plans and programmes to the affinities of specific target groups, etc.) is beginning. In reality, there is a change in the physical learning environment. However, despite the fact that the process of transformation of teaching and learning can differ significantly from one higher education institution to another, such developments do not indicate the disappearance of the classical (traditional) mode of academic education. Therefore, for the further effective development of higher education institutions, it is crucial to analyze the impact of the integration of digital technologies on the educational process.

2.1 Digital transformation and higher education institutions (HEIs)

“We live in a ‘digital age’ where niche technology products and practices can rapidly become mainstream features of day-to-day life.” [8]

Digitalization and technological change are the hallmarks of modern education. Digital transformations are becoming imperative in higher education institutions (HEIs) during the second decade of the 21st century. Selwyn [8], in his book *“Education and Technology, Key Issues and Debates”*, emphasizes that transformational changes are beneficial, but also require a certain degree of departure from the already well-established ways of comprehending behavioral patterns. Contrary to the fact of the existence of a standard concept of education, many authors have a different view on the process of “education” and the definition of that term. Therefore, Illich [9] emphasizes that “to learn” means to acquire new knowledge or a new skill. In order to gain new knowledge and skills in an informal environment, the author proposes and recommends alternative schooling, which he calls “network learning”. Namely, Illich's theory “provides access to references to educational objects and resource persons, skills exchanges and peer-matching approaches to learning”, indicating readiness for: learning or unlearning, accepting criticism, and adapting to the contemporary environment. On the other hand, for Bloom [10], the process of learning can be observed through three forms: I “doing” - mechanical and physical skills (the psychomotor domain); II “feeling” - feelings and arguments (the affective domain) and III “thinking” - mental abilities and knowledge (the cognitive domain).

Aristotle, the ancient Greek philosopher and scientist, viewed the entire process of learning as “a holistic process aimed at achieving eudaimonia (human flourishing) through the development of both intellectual and moral virtues”. Moreover, through the prism of philosophy, he viewed the relationship between ethics and education and concluded that “self-actualization through learning and cultivation of a virtuous character”. As early as antiquity, Aristotle pointed to the importance of education and stressed that the possibility of acquiring new knowledge and expanding the knowledge had the consequence of “transforming” children into free and thinking citizens, while on the other hand, unfortunately, into the lowest strata of society, into slaves. As Russell [11] states “the state aims to produce cultured gentlemen who combine the aristocratic mentality with love of learning and the arts”. Furthermore, Aristotle's quote “Those who know, do”. Those who understand, teach”, points out the distinction between “superficial knowledge” and “deep understanding”.

In recent times, numerous studies have examined the impact of digital technologies on the higher education environment. For this purpose, research into its integration became an area of study for many researchers considering the opportunities to improve the quality of education and support new concepts and strategies for the development of the education

system. Namely, it was essential to determine how and to what extent digital technologies work, to align higher education institutions with future concepts and techniques in teaching and management. Furthermore, it is essential to understand and examine the role and importance of digital technology (e.g., online platforms and media communicative tools) in changing educational paradigms and knowledge management. For example, in the research conducted by Castro Benavides et al., an overview of the literature and references related to the terms “digital transformation”, “higher education institution”, or “university” from 1980 to 2019 is presented. [12] The authors emphasize the peculiarities that unite certain universities in an effort to integrate digital technologies. Furthermore, the advances made in marketing and attracting new students stand out. Finally, they conclude that staff members in many relate digital technologies to functions in HEIs (e.g., infrastructure, education, etc.).

On the other hand, research conducted in public HEIs in Greece has shown that DT marketing is gaining a dominant role in the integration of digital technology. The study aimed to ascertain the perceptions and attitudes (explicitly or implicitly) of the heads of administration at Greek public universities on the relationship between the application of digital marketing and the animation of students. Incidentally, the study's attendees were the rectors and vice-rectors of ten representative Greek universities [13].

Digital learning brings together digital technology and teaching practices. Accordingly, digital learning facilitates the possibility of using various digital learning materials. In this way, the use of digital tools and software increases the flexibility of learning and the possibility of providing a quality education level, especially in rural and remote regions (e.g., face-to-face, blended, online). Nowadays, Google Classroom is becoming an effective means for better understanding (improving the access and attention to learning) [14]. Furthermore, an important place in online learning development, are dominated by numerous digital platforms: Zoom, Google Meet, Skype, etc. [15].

Digital technologies and their integration into HEIs have changed in the way the educational system develops. For example, an online questionnaire survey was conducted with a sample of 69 respondents across 16 public and private universities in Kazakhstan to define trends and opportunities in application of digital technologies - social media tools, online platforms, and digital learning platforms [16]. The survey results covering the administration of universities and faculties (rector, vice-rectors, deans, directors, heads) for six thematic outcomes in the teaching process and five thematic outcomes in the emerging challenges indicated the possibility of applying digital technology in the educational process. Namely, their application would lead to improvement in the quality of management, growth of motivation, easier access to electronic resources, materials, and routine tasks, distance learning, and a greater degree of objectivity in evaluation. On the other hand, numerous problems related to security, technical errors, reduction of communication, as well as dependency and evaluation complexity are included. Finally, the

authors conclude that the key obstacles and challenges in redesigning and digitizing the education system are the teaching staff (insufficiently trained), infrastructure (unsatisfactory development), and the internet (uneven access and data security) [16].

Digital transformation and far-reaching changes in higher education are becoming strategic goals in Romania [17], [18]. Namely, the process of digital transformation and increased use of new technologies began before 2020. Ciurea [19] attempted to highlight the state of affairs in higher education at the time, starting with the digitalization trend of “the new digital era”, citing the Government's efforts to find a contemporary solution for practical application, starting with the National Strategy for the Digital Agenda Romania 2020. Furthermore, she pointed to a project that Romania developed with the Executive Unit for the Funding of Higher Education, Research, Development, and Innovation (UEFISCDI), which is unique in terms of its technological approach and European-wide scope. However, it's worth noting that a group of authors [20] analyzed which digital tools are used daily in higher education institutions in Romania. Incidentally, higher education institutions had minimal prior experience in the use of digital tools and services before Covid-19. Accordingly, the research included interviews with IT chief officers at the top five universities and a survey of the 15 most important Romanian universities to understand and clarify the changes that occurred in teaching and procedures resulting from the integration of digital technologies. In particular, Moodle and Microsoft Teams tools have become very important in the college and university environment (e.g., hybrid learning models).

2.2 Social media and higher education

“.....while it is true that social media promises to enrich the learning experience, the question is clearly about the many ethical and practical issues it raises and therefore requires a most considered and strategic planning for integration within educational setting.”

(Selwyn, 2016, p. 137)

Nowadays, social media has become the initiator of the transmission of information, knowledge, and promotion in educational institutions, especially after the crisis caused by Covid-19. There has been a change in the way of communication and the relationship between users and institutions. In fact, new technologies are being integrated at an incredible rate, allowing “every person to have a platform to engage with others and give feedback easily” [21].

Conducted research indicates that higher education institutions (public and private colleges and universities) are showing particular interest in social media and its integration into higher education. Additionally, perceived usefulness, ease of use, social impact, and facilitating conditions become essential elements for the adoption of social media in the

digital learning environment. In principle, new opportunities in teaching and learning have been created, considering that social media platforms are becoming the most important channels of communication with current and potential students. Moreover, numerous social media platforms (Facebook, Skype, WeChat, Google Drive, YouTube, TikTok, Twitter, Instagram, WhatsApp, websites, and blogs) enable the production, use, and sharing of educational content.

Previous research and available literature have highlighted the existence of a certain level of confusion in defining social media. Some authors underline that social networks and media are free spaces for students to critically evaluate content and information, make different assessments of available information and data, and actively participate in discussions on platforms, and to promote critical thinking [22]. In contrast, other authors highlight “as practices, activities, and behaviors among societies of people who collect online to participate in information, opinions, and knowledge using conversational media” [23]. Dabner defines social media as a technologically advanced tool and devices (internet and mobile-based) representing a combination of technology, telecommunications, and social interaction in one. This type of integration enables the creation, co-construction, and further dissemination of written words, images, and sounds [24]. In contrast, Boyd & Ellison defined social media platforms as a service (based and available on the web) available to an individual to create open or semi-profiles on applications, to communicate with a list of users with whom they wish to communicate and share content, and conversely to view their content located in the monitored system [25].

Numerous authors point out the existence of a positive impact of social media on the learning process (e.g., greater success, increased interaction and collaboration; greater engagement; increased motivation). Unfortunately, social media has also shown to have certain drawbacks (e.g., privacy issues, technical issues, data security, student interference, etc.).

In 2013, a study was implemented at universities in Poland to determine the factors that are crucial for establishing communication in the relationship of higher education institutions - the external environment through social media. The obtained research results indicated the importance of using social media in order to further develop relations with the internal and external environment. [26]. Also, during the 2017-2018 academic year, a study was performed at Spanish universities (at different levels of study) related to the students' perception of the usage of social media in classroom education. The research project “*Media competencies of citizens in emerging digital media in university environments*”, supported by the Ministry of Economy and Competitiveness of Spain, involved 897 students and four focus groups in Seville, Madrid, Huelva, and Barcelona. The conclusion was that students' usage of social media in education and creativity is at a very low level (mainly WhatsApp, then Facebook and Instagram); they value direct and immediate communication, although there are concerns about security (distraction; violation of

privacy by teachers, etc.) [27]. Furthermore, in Malaysia, research was conducted on HEIs via social media regarding the impact of their content on student enrollment, using 231 questionnaires (provided via Google Forms to prospective students). Analysis of metrics (likes, comments, retweets, etc.) and evaluation of the effectiveness of social media content for student enrollment indicate their essential importance [28]. At the same time, a study from Greek universities analyzed the usage of social media, with the aim of improving the curriculum after the Covid-19 pandemic. At the same time, a study conducted at universities in Greece analyzed the use of social media with the aim of improving the curriculum after the Covid-19 pandemic. The author also intended to contribute to the literature in this field. The pilot study data were collected by surveying forty-eight (48) students via a structured questionnaire (consisting of 11 questions) using Microsoft Forms. The results indicated students' agreement that social media should be applied in the classroom, with teacher guidance (it would create conditions for innovation and help in sharing knowledge). Facebook, YouTube, and Instagram were the most popular social media platforms, and would also help teachers in the classroom [29]. Incidentally, in Saudi Arabia, based on the research done (including 221 marketing educators from HEIs; group using social media tools; control group with traditional approach) on the benefits of social media in transforming marketing education, the results indicated their effect in significantly increasing student participation and retention of knowledge. Also highlighted are ease of use, institutional support, and effectiveness in achieving instructional goals. The relevant condition included the preparation and support of HEI members [30].

2.3 Digital transformation and higher education in Serbia

Technological advancements and digital technology have led to changes in the education system that are crucial for transition economies such as Serbia. Thanks to modern trends and innovative solutions, there has been a digital transformation, with methods and tools creating positive changes in e-learning. The process of integrating digital tools has been accelerated during the Covid-19 pandemic (e.g., use of e-learning, virtual reality, smart boards, 3D printing, etc.) [31].

Today, digital literacy is gaining increasing prominence. Therefore, some authors point to its variability and dependence on numerous factors such as the state of infrastructure, the age group of users, the area or region, and the state of the educational system. Others point out that the inclusion of digital technology in the educational system requires constant innovation, both for users (e.g., students, pupils) and for teaching staff (constant training, data protection, maintaining balance). Moreover, particular authors conclude that digital technologies are present not only in the teaching process (leadership), but also in its organization (learning) and other activities (supervision, control, monitoring). In fact, they indicate that the benefits of digital education are realized through an innovative approach and mitigation of future problems in the educational process (e.g., technical barriers,

reduced interactivity). Finally, some research results indicate the need to apply continuous measures for more efficient and effective digital education, including the pupils' education in primary schools [32].

In accordance with the strategic goals defined by the Government of the Republic of Serbia, *the Ministry of Education*, from 2018 to mid-2023, the project, entitled “Connected Schools Programme”, was implemented. Operating along with other ministries (especially the Ministry of Information and Telecommunications, which was the leader of the project), the project aimed to provide almost 100% wireless internet coverage and to connect all primary and secondary (high) schools on the territory of the Republic of Serbia to one safe and secure network. The digital transformation was accomplished by ensuring reliable and good quality internet connections, which was in essence the main prerequisite for the further digital transformation and implementation, and providing implementation of the E-textbook, student information system - electronic student register, and digital virtual classrooms. During the implementation of this project, the Ministry has been working on establishing a PPP (public-private partnership) model, which was also supported by international financial institutions such as the International Bank for Reconstruction and Development (IBRD). The public-private partnership was organized in the following way: [33].

- The Republic of Serbia has built the necessary network infrastructure - the so-called “mid-mile network” (optical network) to central points (primary schools, local self-government units, and local communities);
- Private partners (telecommunication operators in Serbia), who further expanded their network (“last-mile segment”) to rural geographical areas, offering their services and products - internet, mobile, and fixed telephony services.

Operators are selected through public tenders and calls issued by the Ministry of Information and Telecommunications. The rights and obligations of the operator are regulated by the contractual relationship for a period of 25 years. This approach, with the participation of the largest operators operating in Serbia (Telekom Srbija, Telenor/Yettel, and A1 Srbija), has enabled competitiveness and network coverage of different regions in Serbia. [33].

Furthermore, driven by technological advancements and digitization, and based on reliable data (from official institutions such as the *Ministry of Education and the National Body for Accreditation and Quality Assurance in Higher Education - NEAQA*), the study was performed that examines the development of e-education. The research covered all universities, faculties, academies of applied studies, and colleges in the Republic of Serbia. The combined results showed that technological progress and digitization have a great importance and positive impact on the development of E-education in Serbia [34].

Observations in Serbia concerning the use of various tools of “technology-enhanced learning” (TEL) have called attention to the need to modernize and improve educational processes through technological progress. For example, *the Faculty of Sciences* in Novi Sad, for just over two decades, has been implementing numerous modern educational software systems and tools. Accordingly, students were able to use the Moodle platform with broader personalization functions (in general for accessing shared knowledge sources; exchanging educational material, other students' activities, and resources, etc.), as well as during laboratory exercises. Likewise, students at *the Faculty of Technical Sciences* in Čačak and *the Faculty of Pedagogy* in Sombor were able to use this platform in their educational process [6].

Some studies' findings suggest that there is an increase in the daily use of social media (platforms) in the process of education among the student population, and also among primary and secondary school students since 2005. The Vidas-Bubanja [35] study indicated that Serbia was at the beginning of the development of the information society and digital economy. The author, in particular, speaks about the role and importance of education in the process of digital transformation and states that the advantages of new technologies bring stable and profitable business and long-term development of the national economy.

Between 2020 and 2025, a wealth of research has been performed concerning the implementation of social media platforms in education at HEIs in Serbia. According to Trajković [36], a survey conducted among journalism and communications students (100 students) on the use of Instagram for educational purposes at *the Faculty of Philosophy*, University of Nis, in 2020, indicated that Facebook is the most convenient platform, while Instagram is not so important for studying, education, and learning. Notably, almost all students were active on social media on a daily basis (most had a Facebook account, although they used Instagram more frequently).

Primarily, to determine the role of social media in teaching, at the *Academy of Technical - Art Professional Studies in Belgrade - the Department of Management, Design and Textile Engineering* in Belgrade - the Department of Management, Design and Textile Engineering conducted a pilot study on the effects of online teaching in the field of information technologies during the Covid-19 pandemic. The teaching process was performed via Google Meet, Google Classroom, and Zoom platforms. The research aimed to determine and analyze students' attitudes about online teaching in the field of IT. Bulatovic [37] states that the analysis performed yielded answers to the questions: “Is the material of information technologies explained interestingly, through social media?” “Do students recognize social media and communication channels as useful tools for learning materials?”, “Does the use of educational social media in the classroom change the way of communication and collaboration among students, but also between students and teachers?”.

In fact, the survey results showed the existence of a certain degree of student satisfaction with teaching (IT) realized on the social platform Google Meet (for 24.9% of respondents,

there was a high degree of quality; 35.7% of respondents consider Google Meet a useful tool for online learning; 8.4% of respondents easily followed online classes). The author highlights the positive effects of online teaching, recommending further enhancement and elimination of shortcomings.

In 2022, students' perceptions of digitization and the current situation at five state faculties of the University of Belgrade and Tirana were examined [38]. A total of 71 students participated in the survey, 31 from Serbia from *the Faculty of Political Sciences, Faculty of Organizational Sciences, Teacher Education Faculty, Faculty of Economics, and Faculty of Philosophy*. It has been shown that more than half of the students have difficulties in understanding digitization. Also, students believe it is necessary to improve the faculty's digital infrastructure and to implement training to develop and enhance digital skills among all active members of higher education (e.g., students, teachers, administrative staff, etc.).

In 2023, the perception of students (314 students) regarding the use of social media on undergraduate studies (all bachelor years) at the Faculty of Philosophy in Niš was examined in the study programs Psychology, Pedagogy, Social Policy and Social Work, Communication and Public Relations, and Journalism. It is shown that students can communicate and exchange ideas, materials, and resources through platforms such as Facebook, Twitter, LinkedIn, and many others. Analysis and discussion of the survey results indicate the existence of a positive attitude among a greater number of students toward the use of social media in higher education. In fact, there are no statistically significant differences in respondents' responses to independent variables such as years of study, study program, average grade, and time and frequency of use of social media platforms. In this sense, the results obtained can be the foundation for future research and the subject of interest in practice in this field [39].

Accordingly, the Strategy for digital skills development in the Republic of Serbia from 2020 to 2024 (*"Official Gazette of the Republic of Serbia", No. 21/20*) was adopted, which does not list "digital education" as one of the main priorities. As stated, the strategy offers the implementation of digital technologies to improve the quality of teaching and learning. On the other hand, the Strategy for the development of information society and information security in the Republic of Serbia for the period from 2021 to 2026 (*"Official Gazette of the Republic of Serbia", No. 30/18*) mentions "E-education", and initiatives have been implemented or launched for its improvement in the areas of higher education.

In this sense, the National Youth Strategy for the period from 2015 to 2025 (*"Official Gazette of the Republic of Serbia", No. 22 of February 27, 2015*) also does not mention the development of "digital education" and "digital skills" of students. It is worth noting that neither the Law on Higher Education (*"Official Gazette of the Republic of Serbia", No. 88 of September 29, 2017, 27 of April 6, 2018 - other law, 73 of September 29, 2018, 67 of September 20, 2019, 6 of January 24, 2020 - other laws, 11 of February 12, 2021 - Authentic Interpretation, 67 of July 2, 2021 - other law, 67 of July 2, 2021, 76 of September 7, 2023,*

19 of March 6, 2025) contains provisions concerning “digital education”. Finally, “digital education”, in addition to the implementation of digital technologies to improve the quality of teaching and learning, the Strategy for the Development of Education and Upbringing in the Republic of Serbia until 2030 (*“Official Gazette of the Republic of Serbia”, No. 63 of June 23, 2021*) also integrates measures focused on digital competencies of teachers and students.

3. Methodology

The appropriate methodology and data collection strategy are defined. The research data were collected using questionnaires. The paper applies a descriptive method familiar in the social sciences that involves describing concepts based on collected and processed data. The data were analysed and interpreted using SPSS, and appropriate tests (ANOVA, T-test) were used to better understand the collected data.

3.1. Data

In order to collect the data, a survey questionnaire was designed that included three groups of questions: the first group - demographics (age structure, gender); the second group - students' perceptions of social media use; and the third group - exploring the role of social media in HEIs.

The survey was conducted electronically.

This research included 300 students from three faculties (Faculty A, Faculty B, Faculty C) during the 2024-2025 academic year. The participation in research was on a voluntary basis and provided conditions of anonymity, which the students were informed of in advance.

3.2. Limitations

Several limitations were identified during the research.

The first restriction is related to the number of higher education institutions that are the subject of the research (not all universities in the Republic of Serbia are covered by the research). For this reason, the obtained results cannot be generalized, and the existence of critical thinking regarding social media is highly challenging to prove. It also makes it difficult to compare with studies conducted in other countries. This limitation refers to the chosen research method, which has its own limitations due to the (dis)honesty of the respondents. The restriction may also apply to poor-quality questionnaire completion that objectively requires a long time. A disadvantage may be that some respondents did not answer all the questions, especially those requiring “more time to respond”.

The second limitation relates to social media knowledge and literacy. The universities being surveyed have a public relations and communications department. In fact, knowledge and understanding of social media differ among different groups (both from the students' and from the university's side).

The third limitation is connected with the source of data on this topic, which is new and so far insufficiently researched.

A fourth limitation is related to the organization of data collection (one of the weaknesses of quantitative data analysis). This limitation relates to the available resources and knowledge of new trends and innovations (a decreasing trend exists, if the respondents are well informed and prepared about the subject of the research). The risk is accidental questionnaire filling or guesswork. To avoid this type of risk, the questions are structured in a way that they are simple and easy to understand for users.

The fifth limitation relates to AI technology. How is AI utilized to transform the HE and influence Enrollment Management?

4. Results and discussion

The study encompassed an average of 65% of male respondents and 35% female respondents for all three faculties (more men participated). The demographic profile of the respondents is shown in Table 1, and the results of the respondents who participated in the survey by age group are shown in Table 2.

	Faculty A	Faculty B	Faculty C
Male (%)	62	66	67
Female (%)	38	34	33

Table 1. Demographic characteristics of the respondents
Source: Created by authors

	18-20	20-29	30-35
Faculty A	12,30	49,20	38,40
Faculty B	12,40	52,20	35,40
Faculty C	15,30	65,30	19,40

Table 2. Age structure of respondents
Source: Created by authors

Most of the respondents were in the 20 to 29 age group. In the second group, the subjects were aged 30-35, and in the third, they were surveyed in the 18-20 age group. The proportions of respondents by gender and age group for all three faculties are similar.

Figure 1 shows the results of the analysis of the students' perception of social media: 56.3% use for social networking, 30.19% for social targeting/scheduling/strategy, 20.13% use only as an “entertainment” tool (sharing/comments/engagement), and 16.10% indicate their most significant role/impact (role of social media), supported by theoretical analyses (literature data).

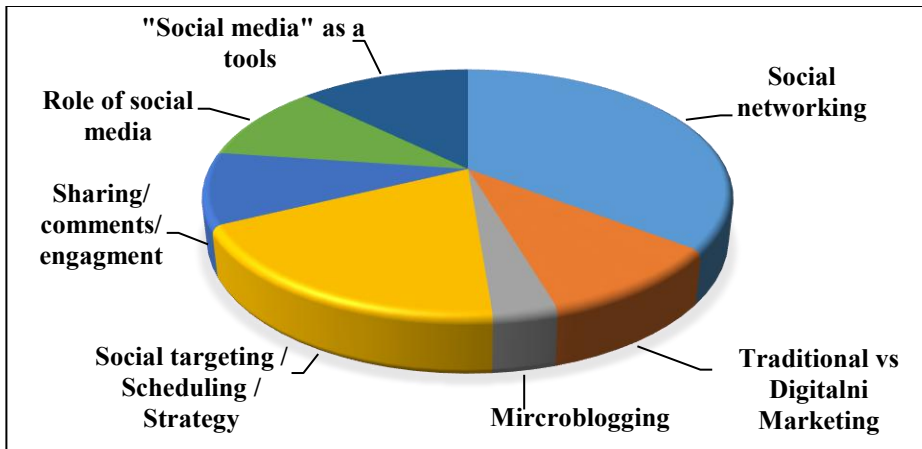


Diagram 1. Students' perception of social media
Source: Created by authors

The results showed that 92% of respondents used some form of social media: Instagram was the most popular, followed by Facebook, Twitter, and lastly Google. Other networks, such as LinkedIn, were mainly used for professional purposes and to learn about new trends (microblogging).

After identifying the type of media that respondents use the most, the research sought to establish the reasons for and the motivations behind their use (Diagram 2). Three categories are presented: only 5% of respondents use it for research, slightly more than 15% for studying and connecting with other professional matters, and the biggest part 80% use it for personal reasons.

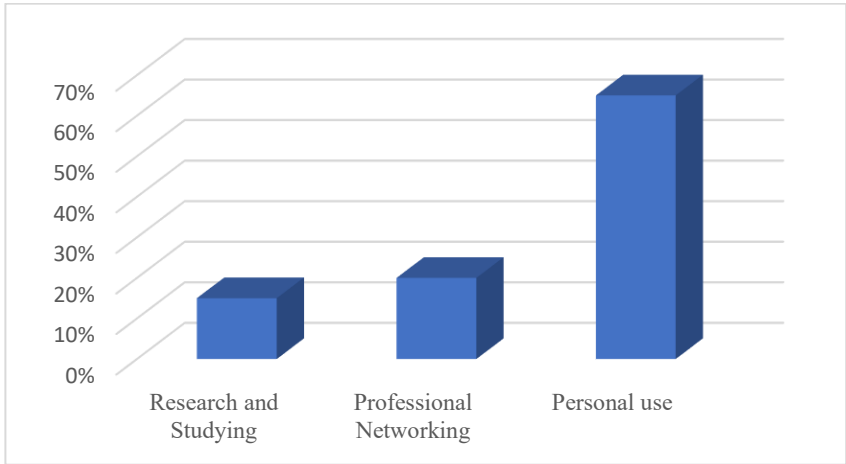


Diagram 2. Reason for using social media
Source: Created by authors

In response to one of the questions, “*Where would you like to use social media in teaching?*” 25% of the respondents answered that they would like to use it for exercises within the teaching process, about 20% for seminars and courses, and 15% for lectures. However, less than half of the participants stated that they would not like to use social media for research, exercises, or similar situations.

Furthermore, approximately 45% of respondents indicated that they would like to engage with educational content via social media, while 65% of respondents approved social media usage for the purpose of promotion, recruitment, and building a better image of the faculty. Thus, some social media tools, such as Twitter, would be beneficial for exchanging new ideas and having better interaction with the teaching and administrative staff (24 hours). Also, only 20% of respondents pointed out that universities need to train their employees to exploit the maximum potential provided by social media (advantages and prospects). In this sense, the technological difficulties that arise due to the lack of technical training would significantly reduce the efficiency of the learning process and academic interaction.

To facilitate a better understanding of results, the ANOVA test was performed for all three faculties. The data are shown in tabular form (Table 3). The results helped to understand the current situation on the use of social media for academic purposes and the extent to which they contribute to the development of higher education institutions (whether they enable improvements in communication and services provided to current and potential students). They also provided an understanding of the statistical differences between groups and how significant they are.

ANOVA Summary for 3 Faculties						
Question	Faculty A (F)	Faculty A (p)	Faculty B (F)	Faculty B (p)	Faculty C (F)	Faculty C (p)

Q14	0.412	.580	0.545	.445	.003	.954
Q15	0.371	.171	0.312	.523	.930	.634
Q16	1.451	0.033	6.607	.003	.078	.028
Q17	1.000	0.010	0.689	.019	1.014	.047
Q18	4.101	.075	.459	.043	1.765	.019
Q19	.500	1.023	0.689	.346	.570	.812
Q20	0.615	.318	0.516	.145	1.432	.024
Q21	1.515	.028	1.516	.012	8.374	.005
Q22	0.771	.690	.312	.590	.399	.153

Table 3. ANOVA test - all three faculties

Source: Created by authors

Table 3 shows the F-value and p-value values for Q14-Q22 questions of relevance to social media from a faculty perspective. Based on the data, the authors concluded that there are statistically significant differences in the respondents' responses as well as similarities between the groups studied. For all three faculties, the differences between the groups were not statistically significant, meaning that the answers to questions Q14-15, Q19-Q20, and Q22 were relatively similar. Based on this, it was concluded that the respondents gave identical answers as to how and in what way they communicate with the faculty departments, and how satisfied they are with the social media provided by their faculty. Regardless, there was a difference in the given answers to questions from Q16 to Q18. and on Q21, indicating the existence of statistically significant differences between the groups (for each faculty), indicating that the respondents' answers differed significantly.

There was a change in the respondents' attitude towards the idea that social media is just a tool for advertising and entertainment. Furthermore, it is indicated that social media is a key factor in the efficiency of communication between universities and students, in the overall process of transforming the learning process.

The respondents felt that some issues required special attention, and were concerned about integrating social media into higher education. For issues related to ethics, data privacy (cybersecurity), and potential cyberbullying, HEIs must define rules and provide support for social media to be promoted and used responsibly [40]. Respondents pointed to the way the faculty uses social media and incorporates it into its “daily activities”, including appropriate staff training and resources available to the faculty. In general, keeping in mind that there are positive and negative influences of social media on the academic educational space, the process of implementation itself is very complex. Most respondents believe that social media has a positive impact on their “academic growth” (support in the studying process). On the other hand, the positive research outcome emphasized the importance of maintaining a balance and a “personalized strategy” between social media and HEIs, but

also the fact that HEIs themselves can influence students' academic success in different ways (e.g., through the offer of innovative techniques) [41].

The research showed that the age group of respondents from 20 to 29 years old, students of Generation Z, use social media the most (also known as “Zoomer”, born between 1997 and 2012). In fact, they are considered digital natives, adults in the digital age (the age of the Internet, smartphones, social media). Throughout their early childhood, members of Generation Z are conversant with modern technology, its role and meaning in practice (technologically savvy), its application (they use mobile applications), the way of communication (open to conversation on social media platforms such as Facebook, Instagram, and YouTube), and a pragmatic approach (financial matters). Considering the fact that this group has unlimited access to information through the media, their attitude reflects an innovative approach to learning: technology becomes an integral part of their education and a key resource for effective learning (e.g., interested in participation and collaboration in content creation) [42].

5. Conclusions

Based on the available literature and conducted research and studies, attention has been drawn to the rapid technological changes and the need for highly technologically competent and skilled people. In practice, the results point to the existence of barriers to the reform of the educational process in higher education, and refer to the insufficient development of infrastructure, untrained teaching staff, and uneven provision of Internet access. Specifically, the transition from the traditional to the innovative method of teaching requires the integration of digital technologies into the teaching process.

Today, social media is becoming an integral part of everyday life. The digital age of social media and smartphones gave universities and colleges the capability to choose to use the new “online environment” to select their users (students), which had previously been done traditionally. Also, the use of digital technologies is becoming significant in the promotion of higher education institutions. Regardless, the main problem is how to adapt this tool to higher education and, in the meantime, improve student satisfaction.

This study included 300 students from three faculties during the 2024-2025 academic year in Serbia related to the students' perception of the usage of social media in education. The research encompassed an average of 65% of male respondents and 35% female respondents for all three faculties (more men participated).

The results indicated students' agreement that social media should be applied: 25% of the respondents answered that they would like to use it for exercises within the teaching process, about 20% for seminars and courses, and 15% for lectures. However, less than half

of the participants stated that they would not like to use social media for research, exercises, or similar situations. 92% of respondents used some form of social media: Instagram was the most popular, followed by Facebook, Twitter, and lastly Google. Other networks, such as LinkedIn, were mainly used for professional purposes and to learn about new trends (microblogging). The age group of respondents from 20 to 29 years old, students of Generation Z, use social media the most.

Future research should focus on finding solutions to improve infrastructure, teaching staff training, and data security, as well as getting comprehensive answers on how universities in Serbia will enhance social media tools and what benefits will be realized by their application in the future.

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INTEGRATION OF MODERN INFORMATION TECHNOLOGIES INTO THE FINANCIAL-ACCOUNTING SYSTEM OF THE ECONOMIC ENTITY: OPPORTUNITIES AND RISKS

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Abstract

The integration of new information technologies into the financial-accounting management system of an entity is essential for improving the efficiency, accuracy, and transparency of accounting processes. The rapid and effective adoption of these technologies can transform the accounting profession, positioning professionals as trusted advisors to top management and contributing to the success of entities in the digital era. Integrating information technologies into financial-accounting information management systems is a defining factor in the evolution of the accounting profession in the digital age. The adoption of these technologies not only enhances the efficiency and accuracy of accounting processes but also significantly contributes to improving organizational performance and decision-making capabilities within entities. An applied model is proposed, focusing research on current issues related to the e-Invoice system (eFactura) and the pre-filled VAT return provided by ANAF, using new solutions for resolution through the integration of blockchain technology.

Keywords: : financial-accounting system, artificial intelligence, cloud, blockchain, decision-making process, e-Invoice, e-Settlement

JEL Classification: M41

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1. Introduction

The accounting profession is undergoing rapid transformation, largely due to productivity gains facilitated by new technologies. In the near future, accountants will be freed from repetitive, process-oriented tasks. Information technology enables the automation of many accounting processes, thereby reducing human errors and saving time. Accounting software automates tasks such as transaction recording, account reconciliation, and financial report generation, allowing accountants to focus on activities considered strategic. Over the past decades, technology has radically transformed the way accounting activities are conducted.

Artificial intelligence (AI) and robotic process automation enable the automation of complex and repetitive tasks and processes with remarkable accuracy, thus reducing operational costs and increasing efficiency. In the digital era, AI and big data have revolutionized many fields, including accounting. The integration of AI with big data allows accounting firms to analyze vast amounts of unstructured data that were previously impossible to manage. According to Marr (2020) [1], "big data has fundamentally changed how companies manage and analyze financial data, enabling a deeper understanding of economic performance and risks." Artificial intelligence, especially machine learning algorithms and natural language processing, plays an important role in managing and analyzing big data. According to Gepp et al. (2020) [2], "AI-based automation and natural language processing are transforming accounting by reducing human errors and providing more accurate and detailed analyses."

Cloud technology has become a necessary component in the development and operation of financial-accounting information systems (FAIS). This technology offers numerous advantages, including improved accessibility, cost reduction, scalability, and enhanced security. Cloud-based systems allow users to access financial and accounting data from anywhere at any time, as long as there is an internet connection. This facilitates remote work and collaboration among geographically dispersed teams. According to Smith (2020) [3], "cloud technology enables accountants and managers to access necessary information in real time, thereby improving decision-making and operational efficiency." The implementation of cloud solutions can lead to a significant reduction in infrastructure costs. Companies no longer need to invest in expensive servers and storage equipment because cloud service providers offer scalable solutions based on a pay-as-you-go model. The use of cloud technology in financial-accounting information systems brings numerous benefits. However, entities must be aware of associated challenges, such as connectivity issues, recurring costs, and data security concerns.

Although blockchain technology might seem like just another trendy business term that could fade over time, accountants cannot afford to ignore it. Blockchain has already been integrated into the field of accounting and is expected to continue playing an important role. It is mainly used for the secure recording and distribution of transactional data, thus offering significant potential for professional development as a reliable tool for tracking financial-accounting information.

2. Literature review

Advances in digitization and the development of information systems, combined with increased competition in the business environment, have significantly influenced organizational activities by eliminating manual labor and excessive paper use for presenting

relevant information. Financial-Accounting Information Systems (FAIS) contribute to monitoring and planning daily activities, allowing managers to obtain a clear and accurate picture of the entity's status. These systems enable users to efficiently plan resources, reducing waste and inefficient usage. In their architecture, information systems have become indispensable for the daily operations of entities, playing a role in improving the flow of information and the decision-making process.

The growing volume of data and documents that need to be processed in shorter timeframes, along with organizational growth, have led to the intensive use of information systems. Another reason for implementation was to provide the "possibility to meet organizational objectives in real-time" (Bordeleau *et al.*, 2020) [4], due to the speed and accuracy with which data is processed. The modular structure of the financial-accounting information system and the integration of processed data into a database allow for more efficient dissemination of information between departments, offering "a correct and complete picture of the entity's situation" (Kanellou & Spathis, 2013) [5].

The necessity of using information systems arises from the increased volume of data and documents that must be processed within a shorter timeframe, based on organizational development. Each component of this system integrates vital functionalities for carrying out the specific activities of each department within the entity, thus ensuring transparency and traceability of the generated information. The Financial-Accounting Information System integrates the entity's processes and functions into a single information system, providing a holistic and integrated view through the use of a unique database. By implementing the financial-accounting information system, entities can benefit from more accurate reports, reduced data processing time, and improved information quality for decision-making.

The influence of information technology on accounting is evident, as this sector is profoundly affected by technological advancements. This brings both challenges and advantages for professionals. Modern technologies enable data processing within shorter timeframes, at lower costs, and with minimal errors—critical objectives for large companies and those providing accounting and auditing services where the data volume is significant (Gonçalves *et al.*, 2022) [6].

The field of accounting is experiencing significant transformations, reflected in innovations in work procedures and how professionals adopt and integrate new technologies. This topic is important because of the considerable influence of technological progress on financial-accounting processes, significantly altering the roles and competencies of professionals in this domain. In the digital age, accounting professionals must be prepared to meet business environment requirements. Beyond the advantages offered by new technologies, they must develop new competencies, understand transformations in their field, and adapt to emerging technologies. Accounting and auditing experts need to develop skills in security to mitigate vulnerabilities brought by new technologies and effectively manage security incidents related to financial-accounting information. Although the security of such information is not a new concept, the context of disruptive technologies has turned it into a contemporary and critical issue.

Today, businesses focus on using and processing large volumes of data, and the role of accountants is increasingly shifting toward data interpretation, overseeing new software programs, and advising clients. In digital accounting, professionals use advanced IT systems based on new technologies throughout the entire accounting process (Andreassen,

2020) [7]. Access to new technologies and data processing solutions enables advanced analyses, complete and rapid data validation, and the ability to share information quickly with clients in a secure IT environment (*Jackson et al., 2022*) [8].

The study of emerging technologies in accounting has been addressed by multiple researchers and academic institutions. *Alles and Gray (2016)* [9] investigated the impact of emerging technologies, such as blockchain and big data, on auditing and accounting. Their work focused on how these technologies can improve the efficiency and accuracy of accounting processes. Kai Larsen, Michael G. Morris, and Majed Moqbel studied the use of mobile and cloud technologies in accounting, exploring how these technologies influence accounting practice and auditing (*Larsen et al., 2017*) [10].

The Assurance Services Executive Committee (ASEC) of the American Institute of Certified Public Accountants (AICPA) has developed several papers and guidelines regarding the use of emerging technologies in accounting and auditing, including the use of artificial intelligence and robotics (*Westland, 2024*) [11]. Accenture and PwC have published detailed reports on how emerging technologies such as artificial intelligence, robotic process automation (RPA), and advanced data analytics are transforming the accounting and auditing industry.

Dietrich and Grüninger (2019) [12] studied the impact of blockchain and other emerging technologies on accounting, exploring both opportunities and challenges these technologies bring. Professors from various universities worldwide have research departments focusing on emerging technologies in accounting and auditing.

3. Research methodology

The study focuses on exploratory and descriptive research aimed at examining and presenting the effects of integrating information technologies into the organization of the financial-accounting information management system. The combination of exploratory and descriptive research allowed for a thorough and comprehensive approach, providing a more detailed understanding of the subject under study. The complementarity of the two research types enabled an in-depth comprehension of the impact of transformations in the organization of the financial-accounting information management system through the integration of information technologies, particularly blockchain technology.

Mixed methods of data collection were used, including documentary research (analysis of specialized literature and relevant resources) and applied research. The analysis of specialized literature and relevant resources involved reviewing and synthesizing studies, reports, articles, and documents pertinent to the research topic. Documentary research provided a robust theoretical framework for the paper, ensuring that the arguments were grounded in existing knowledge.

In addition to documentary research, the paper integrates applied research to obtain concrete data and insights from the practical experience of accounting professionals and domain experts. In this regard, the proposed applied model centers the research on current issues related to the e-Invoice system and the pre-filled VAT return by the National Agency for Fiscal Administration (ANAF), utilizing new solutions for their resolution through the integration of blockchain technology.

By combining qualitative and quantitative research, this mixed-method approach facilitated the achievement of the research objectives and the validation of the established hypotheses.

4. Proposals for Innovative Solutions Regarding the Integration of Modern Information Technology Components within a Financial-Accounting Information System

4.1. Procedure for Accessing Emerging Solutions for Financial-Accounting Information Management

Identifying a reliable solution for managing financial-accounting information that integrates emerging information technologies involves a meticulous process of research and evaluation. To select the most suitable financial-accounting information management solution for an entity, several stages must be followed:

✓ Stage 1 – Internal Requirements Analysis and Objective Setting, which involves:

- *Identifying current issues:* Evaluating existing financial and accounting processes to pinpoint areas needing improvement;
- *Consulting departments:* Engaging with all relevant departments to understand their specific needs;
- *Defining functional requirements:* Preparing a detailed list of requirements such as types of necessary reports, transaction volumes, compatibility with other systems;
- *Setting short-term objectives:* Improving data accuracy, reducing processing time, optimal SAF-T solution, e-Invoice compatibility;
- *Setting long-term objectives:* Scalability, compliance with international regulations, integration with other management systems.

✓ Stage 2 – Researching Available Solutions, through:

- *Technical options evaluation:*
 - ERP (Enterprise Resource Planning) solutions: comprehensive solutions integrating all business functions, including accounting;
 - Cloud accounting solutions: flexible and accessible from anywhere, such as QuickBooks Online, Xero, NetSuite;
 - Automation applications: automating repetitive processes such as bank reconciliations and invoicing;
 - Business Intelligence platforms: analyzing and visualizing financial data to support informed decision-making.
- Consulting reviews and case studies: examining how similar entities have implemented and benefited from these solutions.

✓ Stage 3 – Selecting the Appropriate Solution – involves a complex series of operational analyses:

- *Functionality assessment:*
 - Creating a comparison matrix to evaluate each solution's functionalities against the entity's requirements;
 - Requesting software vendors for demonstrations and trial versions to test the solutions.
- *Cost analysis:*
 - Initial costs: licenses, implementation, training;
 - Recurring costs: subscriptions, maintenance, technical support.
- *Security measures evaluation:*

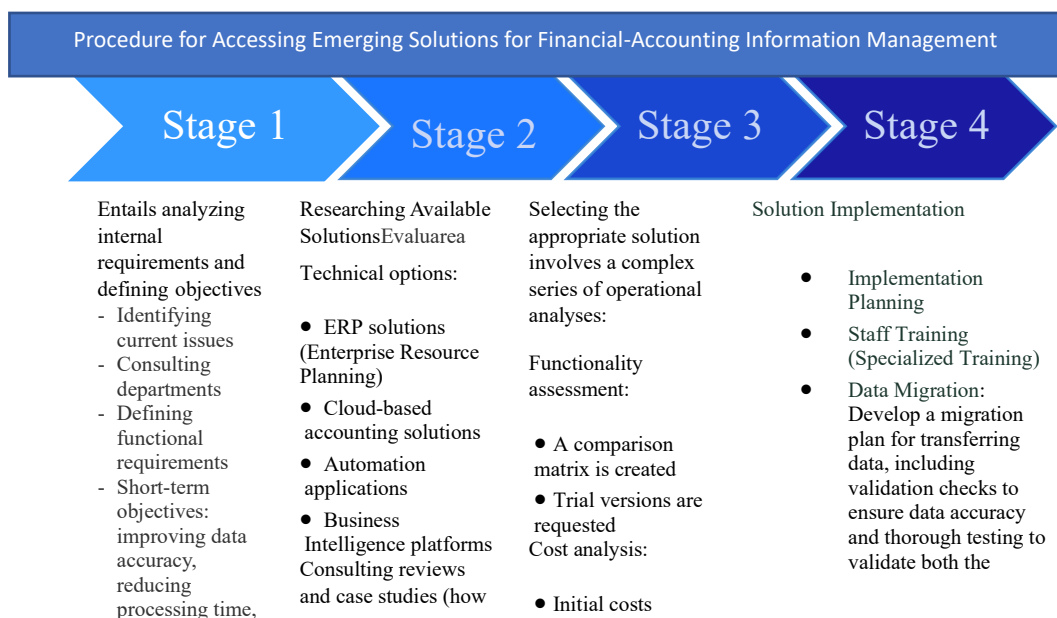
- Data encryption: ensuring the solution provides encryption both in transit and at rest;
- Backup and recovery: verifying backup procedures and recovery protocols in case of incidents.
- *Regulatory compliance:*
 - Checking compliance with national and international accounting standards;
 - Audit and reporting capabilities: the ability to generate audit reports and track user activities.
- *Market analysis:*
 - Monitoring current trends and innovations in the field; identifying key providers and their market shares; analyzing growth forecasts for financial-accounting management solutions.
- *Competitiveness evaluation:*
 - Benchmarking: comparing the performance of selected solutions with direct competitors;
 - SWOT analysis: identifying strengths, weaknesses, opportunities, and threats of each solution.

✓ Stage 4 – Solution Implementation

- *Implementation planning:* Developing a detailed project plan with timelines and allocated resources, clearly defining implementation phases from testing to launch.
- *Staff training:* Including specialized training sessions for directly involved personnel, ongoing support, and resources for troubleshooting.
- *Data migration:* Creating a data migration plan ensuring data accuracy, with thorough testing to validate migrated data and system functionalities.

The conceptual scheme of the procedure for accessing emerging financial-accounting information management solutions within an entity is presented in Figure 1.

Figure 1. Conceptual Diagram – Procedure for Accessing Emerging Financial-Accounting Information Management



optimal SAF-T solution, e-Invoice compatibility	similar entities have implemented and benefited from these solutions)	• Recurring costs Security measures assessment:	migrated data and the system functionality.
- Long-term objectives: scalability, compliance with international regulations, integration with other management systems		• Data encryption • Backup and recovery Regulatory compliance: It is verified whether the solution complies with IAS and/or IFRS standards.	
		Market analysis: Current trends and innovations in the field are monitored.	
		Competitiveness evaluation:	
		• Benchmarking • SWOT analysis	

Source: author's own processing.

4.2. Model for Integrating Blockchain Technology into the Financial-Accounting Information Flow

In the context of financial and accounting activities, blockchain offers numerous advantages. By using a distributed ledger, blockchain enables the secure storage and sharing of financial information among multiple stakeholders, eliminating the need for intermediaries and reducing the risk of fraud. Furthermore, automating processes through smart contracts can streamline accounting operations, reducing both costs and human error.

4.2.1. Proposed Scenario for the Applied Study

The confirmation of invoicing data and payments/collections (CDFPI) is a common way to provide additional security in relation to state authorities and ensures the ability to confirm the truthfulness and authenticity of the transactions performed. This helps reduce the risk of VAT associated with certain invoices becoming non-deductible, among other things. The main function of an accounting system for confirming invoices and payments/collections (SCCFPI) is to prevent situations where an invoice fails to meet deductibility conditions, potentially generating unjustified costs for the entity. To avoid non-deductibility, many accounting ecosystems rely on one or more centralized entities to verify compliance with deductibility conditions. However, this can grant significant power and influence to these entities, making it difficult for users to challenge irregularities, especially when information is incorrectly recorded or intentionally manipulated.

This applied study focuses on current issues in the eFactura system and ANAF's pre-filled VAT return (eDecont), and within this context, proposes new solutions using blockchain technology. A public blockchain can maintain a permanent, secure, ordered, and transparent record of transactions, available at any time to all interested parties for viewing and verification.

In the basic protocol, we proposed an architecture for invoice recording based on a general-purpose blockchain. The blockchain platform builds trust between parties through the correct execution of transactions. We used a smart contract to complete the invoice and payment/collection confirmation process, and to prevent situations that could lead to VAT non-deductibility.

The smart contract includes mechanisms for auditing and dispute resolution to ensure confidentiality while keeping relevant information always accessible. In the second protocol, we added a relay to the proposed architecture for easier integration. We also improved identity management and authentication by using the concept of Verifiable Credentials (VC) to better comply with Know-Your-Customer (KYC) regulations. In this architecture, participants use Decentralized Identifiers (DIDs) and the DIDComm protocol for secure, asynchronous off-chain interactions.

In business-to-business financial relationships, it is common practice to pay for goods or services with a delay, for example, several months later. In this case, the service provider (seller), if using the VAT cash accounting scheme, can defer VAT liability until the invoice is collected. This system provides cash flow flexibility, particularly for small entities.

To implement the system for confirming invoicing data and associated payments/collections, a server will be used that integrates blockchain technology and carries out several procedures to achieve the proposed objectives, namely:

- Payment Confirmation Procedure (PCP)
- Deferred Payment Procedure (DPP)
- ANAF Notification Procedure (ANP)

Each of these procedures has a specific role and will support the proper execution of invoice and payment confirmation.

The Payment Confirmation Procedure is used to notify partners about the collection of payment related to an issued invoice. Upon completion of this procedure, the ANAF Notification Procedure will also be triggered. If one or both entities involved in the transaction apply the VAT cash accounting scheme, ANAF, through the eDecont system, will have the necessary information to accurately pre-fill the VAT return, making VAT liability effective.

The Deferred Payment Procedure establishes a confirmation between the transaction partners, enabling them to mutually confirm payment execution and determine the VAT liability date (for entities using the VAT cash scheme). Upon completing the DPP, the PCP will be resumed to notify ANAF of VAT liability.

The ANAF Notification Procedure is intended to confirm to the authority responsible for the pre-filled VAT return (eDecont) the VAT liability of the finalized and paid transaction. All these procedures will be executed via smart contracts.

The data recorded by the smart contract will ensure high availability of relevant information that the buyer needs to know, such as payment due dates. Because the system handles sensitive data, encryption is applied before storing this data on-chain.

Additionally, a cryptographic commitment of the CDFPI confirmation agreement between the two partners is stored as proof. This summary of the CDFPI agreement stored on-chain can be used to manage future disputes between the seller, buyer, and ANAF. The summary must be signed by both the seller and the buyer.

As mentioned, a CDFPI relationship involves three parties:

- A buyer, which can be an individual or a business entity receiving goods or services on cash or credit;
- A seller, a business entity providing goods or services either for cash or on credit;
- A CDFPI server, which can be a professional accounting association or a state institution (e.g., Ministry of Finance).

Typical interactions between these parties are as follows:

1. Invoice registration in the eFactura system;
2. Receipt from ANAF's server of the invoice validation code confirming its upload to the eFactura system;
3. The seller sells a product or service to the buyer and issues an invoice containing the unique registration code in the eFactura system. The invoice is transmitted to the buyer through the eFactura system as well as physically. The buyer verifies the invoice's registration in eFactura;
4. If payment is made instantly, the PCP (Payment Confirmation Procedure) is triggered, confirming the payment to both parties and activating the ANP (ANAF Notification Procedure).

If payment is made later, the DPP (Deferred Payment Procedure) is triggered, and upon actual payment, the PCP is resumed;

5. Once the payment is made, the ANP (ANAF Notification Procedure) is triggered to confirm VAT liability for the completed and paid transaction to the authority responsible for pre-filling the VAT return;
6. ANAF generates the pre-filled VAT return.

There are multiple issues and challenges in the CDFPI process. For instance, it often requires multiple manual steps. Moreover, data is spread across different systems and databases. There are also trust-related problems in the confirmation of invoicing and payment data.

The seller and buyer must trust that both will promptly update the information needed to confirm payments in a timely manner for ANAF to generate the eDecont. When the buyer confirms the payment, the seller must verify that the transaction was actually executed, as a buyer could confirm payment without actually making it. This is a key issue that a CDFPI system must address to prevent VAT fraud.

Typically, we can assume that both the seller and buyer can only be considered trusted parties when both confirm the transaction payment, as both have an economic stake in the CDFPI process—one deducts VAT, while the other is liable to pay it. In this context, a public blockchain appears to be a natural solution for addressing these issues, as it can track CDFPI processes and also prevent potential fraud. A distributed ledger makes the database highly available, logically unique, and secure against tampering.

Thus, the operations for confirming invoicing data and payments/collections (CDFPI) can be completed faster, with fewer errors, and still retain the authenticity and credibility of traditional manual contracts. Concretely, a CDFPI system based on ledgers should:

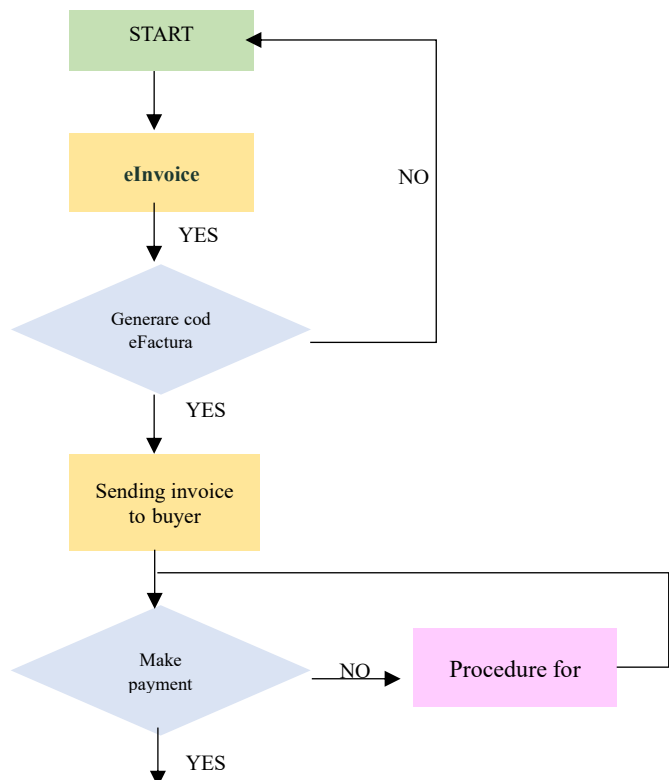
- Operate without errors;
- Provide confidentiality and protection of personally identifiable and business information;
- Offer non-repudiation for dispute management;
- Be decentralized and secure against corruption;
- Comply with KYC regulations;
- Be cost-effective;
- Support easy user integration.

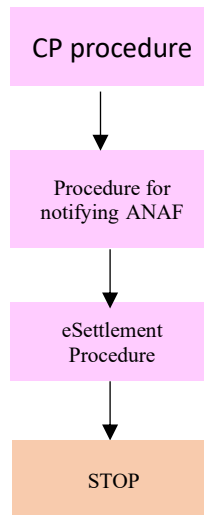
4.2.2. Proposed Architecture

In the proposed architecture, we have the three classic entities of the eDecont scenario - namely: the buyer, seller, and ANAF, a new entity (Payment Confirmation Server), and smart contracts implemented on a public blockchain.

A detailed explanation of the proposal and the associated logic diagram is presented in Figure 2.

Figure 2. Logical Diagram of the CDFPI System





Source: author's own processing.

At a high level, the proposed protocol must operate by following these steps:

- ✓ the seller sends the invoice to the client through the eFactura platform;
- ✓ the seller sends a request to the buyer to confirm the receipt of the claim or to confirm that it will be collected later;
- ✓ the buyer publishes a cryptographic summary of the payment on a web service;
- ✓ the seller waits for the payment confirmation from the buyer;
- ✓ at the time of payment, both the buyer and the seller certify the payment execution via a smart contract;
- ✓ the server sends confirmation to ANAF for pre-filling the data related to this transaction.

In the designed architecture, after verifying the declaration of the invoice to ANAF through the eFactura system, we assume the buyer is trusted for the payment confirmation process. Also, we assume a public blockchain for the proposed architecture, but it should be noted that blockchain cryptocurrencies will not be used for payments. The proposed architecture is a recording system, and actual payments are made off-chain using fiat transfers between bank accounts. All interactions to complete the CDFPI will be managed through a smart contract. All parties can trust the correct execution of the transactions managed by the smart contract because the blockchain platform guarantees this execution.

If the invoice was taken into account, the buyer must pay the invoice into the registered entity's bank account via the smart contract. Therefore, all involved parties must review the smart contract code and ensure its correctness. The smart contract address is also part of the negotiation between the seller and buyer. This is because every transaction that changes the state of a public blockchain has a cost. One of the main objectives of the architecture design is to minimize the number of transactions needed to confirm billing data and payments/receipts. A large part of communications between the different parties occur off-chain.

As a general rule, in the presented design, the CDFPI is kept as simple and resource-efficient as possible for ANAF. In particular, within the proposed architecture, ANAF will not require specific digital certificates for confirming billing data and payments/receipts and will not perform digital signatures related to this process. Instead, the payment confirmation server will provide a simple web service for accessing minimal information about invoices and their related payments. This allows ANAF to verify the information provided by the seller/buyer in the submitted returns.

Another aspect to consider is that when using a public ledger, transparency is gained, but at the same time, all interested parties have access to the stored data. In the process of confirming billing data and payments/receipts, there is sensitive commercial information that must be appropriately protected. To protect privacy, sensitive data is not stored directly on the blockchain. Instead, some data is symmetrically encrypted before being stored on-chain, some data is stored off-chain, and cryptographic commitments are used to provide proof of existence.

Once an invoice and payment confirmation are registered, it is guaranteed that:

- ✓ it has been declared to ANAF and is deductible;
- ✓ it is accepted by both buyer and seller;
- ✓ relevant parties have access to the relevant data and proof of its existence;
- ✓ there is no way to contest the CDFPI once the smart contract has been registered.

Additionally, to perform the registration process, all parties will have real identities (e.g., tax identification numbers), and both seller and buyer will also have blockchain accounts (which are pseudonymous identifiers). Finally, we assume that an invoice contains the following information: seller and buyer identity, invoice number, issue date, payment due date, total amount, and other details about the services/goods provided by the seller to the buyer. We assume that the seller's identity and invoice number are sufficient to uniquely identify the invoice; therefore, the use of unique invoice numbers should be applied. Furthermore, the buyer's identifier, due date, and total amount are necessary for ANAF's pre-filling of the eDecont form. Additional information can be added to the invoice without affecting how the designed architecture works.

The proposed architecture is set in a financial context and is therefore subject to strict regulatory restrictions. In particular, according to Know-Your-Customer (KYC) regulations, involved parties must be well-identified with each other, and their agreements must be maintained for audits and law enforcement purposes. To comply with KYC, the seller and buyer will record the correspondence between their real identity (IDA) and their pseudonymous identifier on the blockchain (@A). We use the term Blockchain Certificate to refer to these links between real identities and pseudonymous identities.

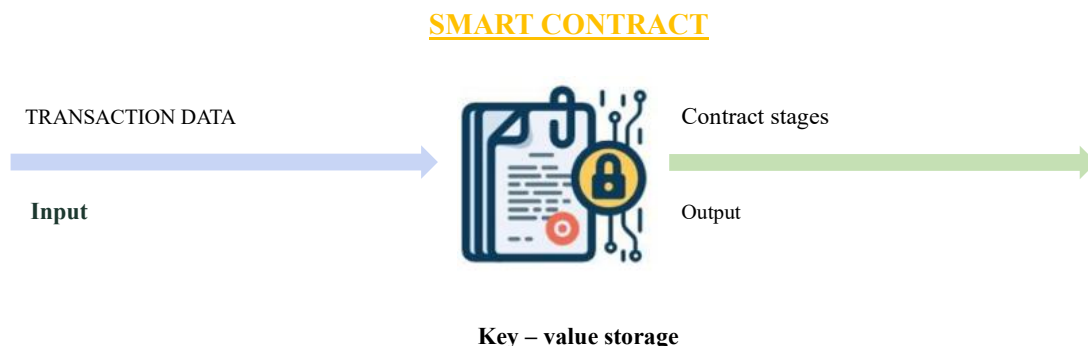
In the proposed architecture, we rely on the buyer and seller to create these links because both should pay/deduct VAT; thus, we assume they have an interest in certifying transactions. On the other hand, by design, the established protocol avoids ANAF digitally signing the Blockchain Certificates or any other data. Blockchain Certificates are used privately and exchanged only between a seller and a buyer after they intend to conclude an agreement. Additionally, an entity can have multiple Blockchain Certificates with different blockchain addresses for extra protection against linkage attacks.

The protocol is built around a smart contract implemented on a public blockchain. The smart contract will contain registration data for a set of invoices. No one (including the deployer) will have special powers over the contract. In particular, no one will be able to

interfere with the smart contract's operation or modify the data of the invoice set and payment terms.

The proposed architecture is designed to operate on a public blockchain. Public blockchains have costs, so the established protocol must be cost-efficient. Generally, there are three different places where data is stored on the blockchain (*Figure 3*): transaction input data, key-value storage, and transaction output logs. Each of these places has a different purpose and cost.

Summary of smart contract storage options:



Source: author's own processing.

The transaction input data are the data within the transaction that provide inputs for executing the smart contract logic for the current transaction. Transaction input data are very inexpensive compared to key-value storage, which is by far the most costly type of storage. Key-value storage provides persistent storage to the smart contract that lasts across transactions. Key-value storage is part of the blockchain's current global state and, as such, can be used by the smart contract logic to execute future transactions.

Finally, transaction output logs are data generated after the execution of a transaction. Both transaction input data and transaction output logs are part of the blockchain data and, as such, are highly available and immutable. However, these data are not part of the blockchain's current global state, meaning blockchain nodes are not required to keep this data in their current state once the transaction has been executed. This is why these data are inexpensive to store and also why log data from a previous transaction is not available to the logic executing a subsequent transaction.

In the presented protocol, we use a combination of the three aforementioned storage locations to provide an efficient implementation while maintaining privacy and security of the architecture. Specifically, we use a single persistent key-value slot to prevent fraud. CDFPI data are recorded using a transaction output log.

It is worth mentioning that transaction output log data usually have indexed fields that allow external entities to perform fast searches based on these indexed fields. In the protocol, we use a pseudonymous invoice identifier as an indexed log field to speed up data lookup.

Data recorded by the smart contract will provide high availability of relevant data that the buyer needs to know, such as the seller's bank account and payment due date. Since a bank

account contains sensitive information, we must encrypt this data before storing it on-chain. Additionally, we store proof of the agreement summary in the form of a cryptographic commitment.

Storing the smart contract summary on-chain can be used to manage potential future disputes between the seller, buyer, and ANAF. This agreement summary must be signed by both the seller and the buyer.

Finally, it should be noted that the smart contract stores the blockchain addresses of the seller and buyer on-chain as part of the transaction registration. In the established protocol, we use transactions that include signatures using the blockchain identities of both the seller and buyer, and we recover their blockchain addresses from these signatures.

The detailed process of the complete CDFPI using the above protocol is as follows:

Phase 1: eFactura registration The CDFPI process for a specific invoice begins with the registration phase and is followed by the payment confirmation phases. Each phase consists of multiple steps, which are described in Figure 1 and explained below. At the beginning of the CDFPI phase, the seller requests the buyer to publish the billing information through their web service. The publication is quite similar to how Blockchain Certificates are published, except that additional information related to the CDFPI process is required.

Phase 2: confirmation of billing data and payments/receipts This phase starts with the seller contacting the buyer to confirm payment or confirm the payment due date. The seller should naturally provide the invoice details, including the invoice number, total invoice amount, and the payment due date to the buyer. Ultimately, we need the invoice registration data to be available to the parties: the buyer for VAT deduction, the seller for VAT payment, and ANAF for eDecont pre-filling, so that all three parties have evidence in case of disputes. To do this efficiently, we store this data as smart contract transaction output logs.

Phase 3: payment In the third phase, after verifying the information registered by the smart contract, the buyer pays the seller. Subsequently, both the buyer and seller will confirm the payment on time, and ANAF will be informed through the notification procedure. If either the buyer or seller is a VAT beneficiary at collection, ANAF will use the data for pre-filling the eDecont.

4.2.3. Dispute Management

It should be noted that our registration protocol is not secure against malicious buyers, because if the buyer and seller publish false information, ANAF can only challenge this after thorough investigations. As a result, ANAF must trust that the buyer and seller will voluntarily comply. A malicious buyer, for example, may fail to pay the seller but still confirm the payment. A malicious buyer may also deceive ANAF by creating a fake seller and a large number of nonexistent invoices. Then, the fake seller receives payment confirmations, but the corresponding payments are not made by the malicious buyer, who commits VAT tax fraud.

If the buyer is not trustworthy, a mechanism should be used to enforce good behavior (such as a publicly available reputation system). On the other hand, a seller may be concerned about a malicious buyer who might withhold payment. In this case, the seller reveals the message sent by the buyer to a court of law. The following steps are then sufficient to resolve the case:

1. Verification of the invoice certificate;
2. Verification of the terms of the agreement;
3. Verification of the seller's address;
4. Verification of the buyer's address;
5. Verification of the signature: the court holds all necessary information about the payment confirmation agreement and can verify the buyer's signature on this information;
6. Determination of the responsible party;
7. Retrieval of registration information from the smart contract and its logs. The contract address is certified, and the judge has the buyer's signature on it;
8. Trial: the buyer will be convicted based on the non-repudiation of digital signatures and the tamper-proof evidence from the smart contract.

5. Conclusions

The motivation for this research was influenced by the difficulty and necessity of adapting to emerging technologies specific to the digital age. Accounting professionals must comply with new requirements imposed by both the external and internal environments, as well as integrate modern information systems that, through frequent updates, provide advanced functionalities and options for intelligent data analysis. In achieving this objective, medium- and long-term trends were identified, highlighting the technical requirements and skills necessary for accounting professionals, and emphasizing the importance of the applicability and functionality of new information technologies.

Digitalization through the use of financial-accounting information management systems, which integrate advanced technologies such as artificial intelligence and blockchain, is crucial for the evolution of the accounting profession in the digital era. Accountants must adopt these technologies to remain relevant and bring added value to their entities, contributing to strategic decision-making and maintaining compliance with the ever-changing fiscal and accounting requirements.

The future of accounting will involve increased adoption of increasingly advanced technologies. Whether referring to artificial intelligence, automation, data analytics, or cloud computing, these innovations will significantly boost productivity and underscore the need for accounting professionals to develop their skills in emerging information technologies. Several aspects deserve attention: technology will support accountants without replacing them, productivity will increase, data security will improve, the most efficient accounting professionals will be those open to change, and while technology will not replace accountants, their roles will evolve over time.

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PROPOSING A MULTI-AGENT SIMULATION FRAMEWORK FOR QUANTIFYING THE EMERGENCE OF THEORY OF MIND IN FOUNDATION ARTIFICIAL INTELLIGENCE MODELS

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Dana-Mihaela PETROȘANU²

Abstract

The ability to reason about others' mental states, known as Theory of Mind (ToM), is an important aspect of social intelligence. Nevertheless, quantifying its emergence in foundation AI models has been hampered by methodological flaws in existing static benchmarks. Current evaluations often rely on single-turn vignettes that are susceptible to dataset contamination and shortcut solutions, making it difficult to distinguish genuine belief reasoning from superficial pattern matching. This paper proposes a multi-agent simulation framework to address this challenge. We embed foundation models as agents in interactive, partially observable environments where success is causally contingent on tracking, inferring, and manipulating others' beliefs. The framework operationalizes ToM through dynamic task families, including false-belief, deception, and coordination games, that make nested belief reasoning very important and necessary for achieving goals. Significantly, this aspect goes beyond purely behavioral outcomes by instrumenting process evidence, such as the alignment of an agent's reported beliefs with ground-truth epistemic states and its subsequent actions. The proposed approach separates intrinsic model competence from the effects of performance artifacts and inference-time scaffolding. The primary contributions are operational semantics for ToM in artificial agents, a suite of belief-critical tasks, and a measurement protocol that integrates outcome success with process-level validation. Applying this framework reveals that while current models exhibit measurable and partially robust first-order ToM-like capabilities, higher-order reasoning is more fragile and strongly dependent on model scale, context, and structured deliberation. By providing an auditable, reproducible, and adversarial robust evaluation substrate, this work establishes a principled methodology for quantifying how and when social cognition emerges in artificial agents, moving the field from unreliable claims toward a cumulative, empirical science.

Keywords: Theory of Mind, Foundation Models, Multi-Agent Simulation, Emergent Abilities, Artificial Social Intelligence, Computational Cognitive Science

JEL Classification: C6, O3, O33, O34, O35, O36

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1. Introduction

In order to engage in rich social interactions, artificial agents must be capable of attributing beliefs, desires, and intentions to others. This capacity, known as Theory of Mind (ToM), is an important element of human social cognition [1]. A pressing question is whether large-scale foundation models, trained on broad internet data, exhibit a comparable ability and, if so, under what conditions and through which mechanisms. Early claims of ToM-like skills in such models have been contested, with critiques suggesting that success on evaluation tasks could arise from dataset artifacts, prompting strategies, or superficial pattern matching rather than genuine belief reasoning. Therefore, the field faces a dual challenge, namely, to establish careful operational definitions of ToM suitable for artificial agents and to create evaluation environments that elicit true belief reasoning instead of allowing shortcut solutions. This work addresses both needs by proposing a framework for measuring when and how social-cognitive skills emerge in AI.

1.1 Motivation and research questions

The drive to quantify ToM in foundation models is motivated by theoretical, methodological, and practical considerations [2,3]. Theoretically, it explores whether large-scale, self-supervised training on human data can induce the latent structures necessary for belief reasoning, a subject of open debate in cognitive science. Methodologically, existing ToM tests for AI often contain serious pitfalls, many rely on simple story puzzles or prompted questions that models might solve via shortcuts, casting doubt on claims of genuine mental state attribution. Practically, foundation models are increasingly deployed in interactive roles where they must infer user intent, negotiate with other agents, or coordinate under partial information. Robust measures of social reasoning are therefore essential to ensure these systems behave safely and predictably [4,5]. Guided by these motivations, our research investigates whether foundation models exhibit ToM-like competencies and, if so, under what conditions. We examine how this capability scales with model size or improves with interaction. A very important goal is to design tasks that necessitate belief reasoning, thereby revealing its presence or absence with high fidelity. Ultimately, our framework is engineered to distinguish genuine belief attribution from clever but still shallow heuristics or memorized patterns.

1.2 Contributions and scope

This article offers a unified conceptual and experimental framework for studying the emergence of ToM in foundation models [2,3], comprising construct definition, task creation, and rigorous evaluation. Our first contribution is to operationalize ToM for artificial agents by providing precise definitions for different levels of belief reasoning and by clarifying what constitutes evidence of such capabilities. In order to elicit and test these abilities, we introduce a suite of interactive multi-agent simulation tasks, including false-belief scenarios and deception games, designed so that success requires the inference and manipulation of others' hidden mental states. This design prevents solutions based on superficial pattern matching. In complementing these tasks, we develop a comprehensive

measurement protocol that combines outcome-based metrics with process-based analyses of an agent's decision-making, offering deeper insight into its reasoning. Finally, through extensive experiments, we map the conditions under which ToM-like abilities appear in foundation models of different scales. Our empirical findings show that while current models exhibit some robust first-order ToM, higher-order reasoning remains fragile, and we identify the factors that influence this performance. Together, these contributions advance the study of social cognition in machines and lay the groundwork for a more rigorous science of machine ToM.

1.3 Definitions of ToM, emergence, foundation models

In order to ensure clarity, this work adheres to precise definitions for its core concepts. We define ToM as an agent's operational ability to represent and reason about the mental states of others, using these representations to inform its actions. This capacity is treated as a graded property, observable through behavior, rather than as a monolithic trait. The term emergence refers to qualitatively new capabilities that manifest at a certain scale of model complexity, surpassing extrapolations from smaller models. In order for a capability to be considered emergent, it must be reproducible and robust. We also distinguish an agent's intrinsic competence from performance enhanced by external scaffolding, such as memory buffers or planners. Foundation models are the large-scale, pre-trained neural networks that serve as the cognitive core for the agents in our simulations. Our framework explicitly separates the abilities of the base model from the contributions of its surrounding architecture.

1.4 Overview of approach and findings

The subsequent sections of this paper systematically unfold our framework (Figure 1). We begin by situating our work within the existing literature before formally defining the problem and our central hypotheses. We then detail the multi-agent simulation environment and agent architecture developed to test these hypotheses. Following this, we describe the specific evaluated foundation models and the comprehensive protocol used for their assessment, including our proposed metrics and statistical methods. Moving forward, the paper presents our experimental results, makes a deeper analysis of model behaviors and failure modes, and puts forward a discussion of the broader implications, limitations, and ethical considerations of our findings. We conclude by detailing our commitment to reproducibility and outlining future research directions.

Our results provide a nuanced picture of ToM in current foundation models. We find that agents can achieve non-trivial performance on tasks requiring first-order belief reasoning, such as tracking another agent's knowledge to succeed in a cooperative endeavor. Nevertheless, robust higher-order ToM, which involves reasoning about nested beliefs, remains largely unattainable with current capabilities. While larger models and specific scaffolding techniques yield performance gains, we also demonstrate that these apparent abilities are often fragile, diminishing significantly under adversarial or out-of-distribution conditions. These findings emphasize both the promise and the current limitations of

artificial social cognition, reinforcing the very important need for the principled evaluation framework we propose [6].

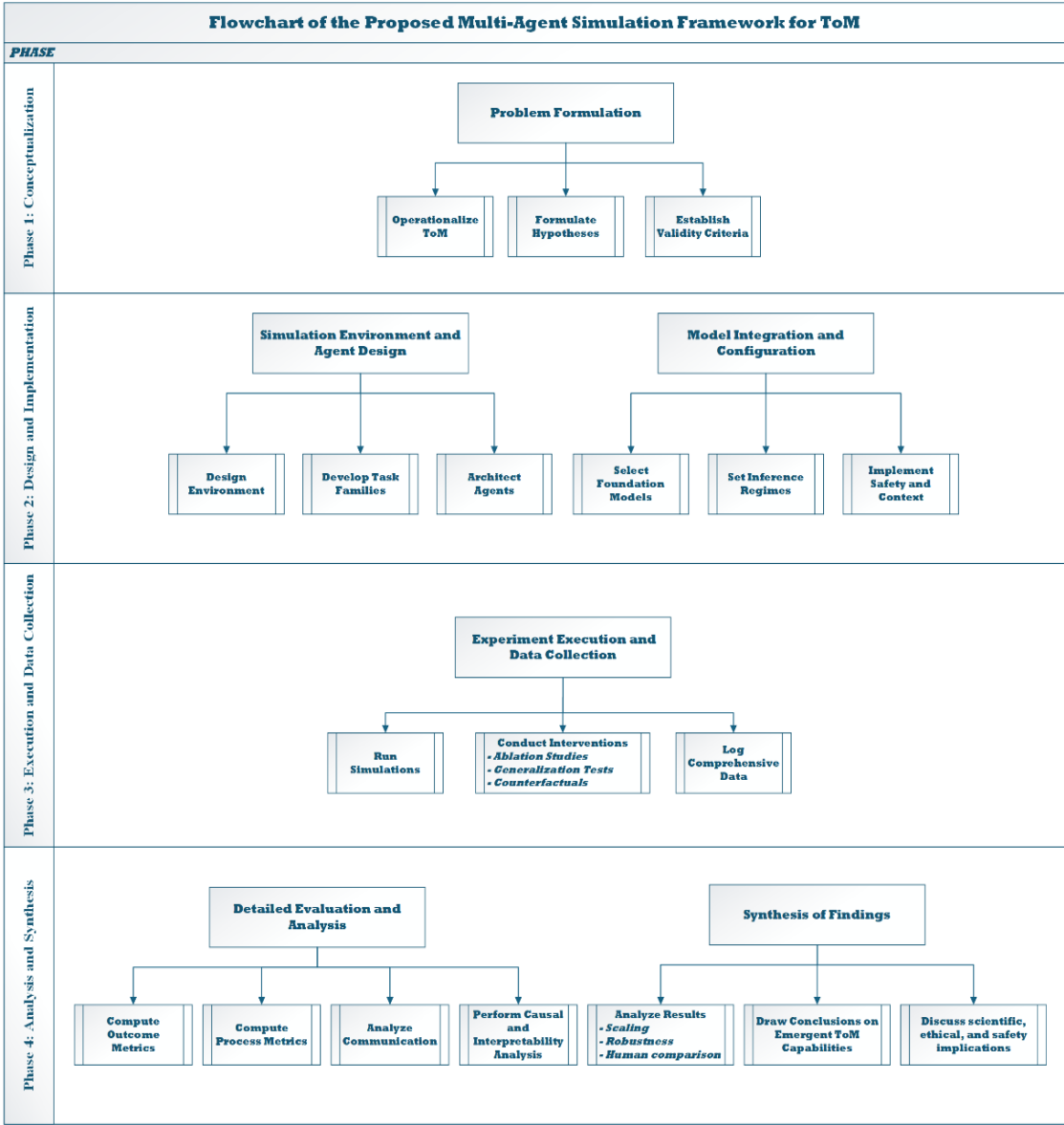


Figure 1. The main Phases and Steps of the Proposed Multi-Agent Simulation Framework for TOM

2. Background and Related Work

2.1 ToM in cognitive science and developmental psychology

The modern research program on Theory of Mind (ToM) originates in Premack and Woodruff's seminal question, "Does the chimpanzee have a theory of mind?", which stimulated the study of mental state attribution in non-human agents [1]. In parallel, extensive research in developmental psychology has documented the trajectory of human ToM capabilities, exemplified by a child's comprehension of false beliefs around preschool age, classically assessed with the Sally-Anne test [7]. Persistent debates in cognitive science address whether human ToM is powered by a specialized innate component, a learned theory-building process, or a simulation of others' minds. These foundational insights inform the evaluation of artificial intelligence. Validating claims of artificial ToM requires grounding them in rigorous tasks and criteria analogous to those used in human studies. Furthermore, developmental delays in ToM, such as those associated with comparative primate studies suggest the involvement of specific cognitive mechanisms [8]. This raises the question of whether an artificial system, lacking analogous evolutionary and developmental structures, can attain similar abilities or is destined to fail in comparable ways.

2.2 Computational models of ToM and belief modeling

These psychological inquiries encouraged efforts to formalize the mechanisms of mental state attribution within computational frameworks. Influential approaches in Bayesian cognitive science treat ToM as a form of probabilistic inference, where an agent maintains a model of others' mental states and updates it based on observations, as seen in rational speech-act models of communication [9]. For instance, an agent might infer another's goal or knowledge by observing its behavior. Other research traditions have explored logic-based systems like dynamic epistemic logic to formally capture knowledge updates, as well as recursive agent models such as the Interactive Partially Observable Markov Decision Process (I-POMDP) formulation, which extends planning to multi-agent belief reasoning by explicitly incorporating nested beliefs into an agent's decision model [10–12]. While these computational models provide normative blueprints for ToM, they typically involve hand-crafted representations or operate in simplified settings, unlike the large, inductively learned models studied in this work. In order to address different aspects of ToM, our framework therefore includes parameterized task families, each procedurally generated to prevent data contamination and designed to make a specific order of belief reasoning necessary for success (Table 1).

Task Family	Primary ToM Target	Core Mechanic	Key Perturbation
False-Belief and Perspective-Taking	First-Order Belief Tracking	Asymmetric observation of object movement or visual	Knowledge Swaps: Exchanging agents' private observation histories while

		occlusion in an interactive world.	keeping surface text identical.
Deception and Signaling Games	Second-Order Strategic Reasoning	Misaligned payoffs in a cheap-talk game where a sender's message influences a receiver's action.	Payoff Matrix Inversion: Flipping incentives from cooperative to competitive to test strategic adaptation.
Coordination and Negotiation	Belief-Guided Joint Planning	Partially observable environments (e.g. mazes, resource allocation) requiring common ground formation.	Partner Heterogeneity: Introducing partners with novel or out-of-distribution communication styles.
Communication-Constrained Settings	Pragmatic and Belief-Sensitive Communication	Imposing costs or bandwidth limits on messages, forcing efficient information transfer.	Bandwidth Ablation: Systematically varying message length limits to measure pragmatic compression.

Table 1: Overview of ToM Task Families and Their Epistemic Demands

2.3 Emergence in large-scale models

The advent of such large-scale models has prompted claims of emergent abilities, which are capabilities that appear to surface once models reach a certain threshold of complexity or training size. Some researchers report that qualitatively new skills, including social reasoning, manifest suddenly as model size increases. An alternative perspective contends that many such instances of emergence are continuous performance gains misconstrued as discrete jumps due to coarse evaluation functions, dataset composition, or the long tail of task difficulty [13]. This view posits that apparent emergence is an artifact of nonlinear metrics or naive extrapolations of scaling curves. We treat emergence as a falsifiable hypothesis about patterns in our data, seeking evidence that ToM-relevant competence

exceeds what naive scaling expectations would predict. Indeed, some scaling-law studies have found smooth, power-law improvements rather than strict discontinuities, suggesting many so-called emergent behaviors might simply require more fine-grained analysis. Nonetheless, the observation that certain abilities, like solving specific logic puzzles, appear to manifest only beyond a large parameter threshold keeps the discussion open. This stance shapes our experiments and their interpretation, namely any reported emergence is supported by statistical evidence beyond a simple parameter-performance curve and validated through replication and perturbation tests.

2.4 Multi-agent simulation for studying social cognition

Investigating such complex cognitive phenomena necessitates robust experimental paradigms. Interactive multi-agent simulations provide a promising opportunity to study social intelligence, creating dynamic scenarios where agents with partial information must interact over time [14,15]. Unlike static question-answer tests, these environments enable the study of communication, cooperation, deception, and the formation of shared conventions. Prior work has demonstrated that multi-agent environments can encourage emergent behaviors like tool use and novel communication protocols.

In the case of ToM research specifically, simulations offer a very important advantage, namely the ground-truth mental states of agents are known to the experimenter, allowing for objective measurement of whether an agent is successfully tracking what others know or believe [16]. This approach inspired our framework, which embeds models in environments designed to require belief reasoning, leading to reproducible data on their social cognitive performance. The use of multi-agent games also permits repeated trials under slightly varied conditions, which is extremely important for distinguishing consistent ToM competence from fortuitous guesses or overfitting [17].

2.5 The strengths and pitfalls of existing ToM evaluations for LLMs

The controlled, dynamic nature of multi-agent simulations stands in contrast to many existing ToM evaluations for large language models (LLMs) [17–19]. The question of whether LLMs possess ToM has led to a wave of evaluation attempts, often using classic false-belief stories or social vignettes. Although prompting techniques like chain-of-thought reasoning can elicit seemingly correct answers, these successes are difficult to interpret. An LLM might arrive at the right answer by leveraging superficial patterns or by recalling similar examples from its training data [18,19].

Reports of advanced ToM in certain models have been contested by findings that slight rephrasings or novel scenarios degrade performance, suggesting a fragile grasp of others' mental states. Existing evaluations are frequently one-off and brittle, lacking controlled difficulty or safeguards against data contamination. This methodological heterogeneity complicates efforts to ascertain whether a given model genuinely possesses ToM-like abilities or is merely exploiting shortcuts. These limitations motivate our controlled, simulation-based evaluation, which aims to provide stronger, auditable evidence regarding belief reasoning in AI. By engaging models in interactive, multi-turn tasks with verifiable

belief dynamics, while also ruling out data contamination and providing robust analysis protocols, we seek to obtain a clearer picture of their social reasoning capabilities [20].

3. Problem Formulation

3.1 Operationalizing ToM (first-order, higher-order, recursive belief states)

This section establishes a formal framework for measuring Theory of Mind (ToM) in artificial agents, specifically those instantiated as policy wrappers for foundation models. The framework specifies the construct, the setting for its elicitation, and the conditions for interpreting measurements as genuine belief reasoning rather than as artifacts of surface pattern matching. This formulation aligns with the multi-agent simulation program where belief-dependent incentives, controlled partial observability, and instrumented communication render mental-state inference causally necessary for success. The entire approach is anchored by several foundational commitments. ToM is conceptualized as a graded, operational construct, distinct from a metaphysical attribute. Emergence is defined by robust, out-of-sample regularities, not by rhetorical discontinuities [19]. Valid measurement must integrate behavioral outcomes with underlying processes. Any claims must be falsifiable through perturbations that selectively impair belief-based solutions while leaving heuristic shortcuts intact. These principles ground the formalism and ensure its scientific rigor.

The formal specification begins by situating agents within a partially observable environment, modeled as a stochastic game, where each possesses unique observations and knowledge. An agent's first-order belief is its internal estimate of the world's state, or task-relevant hidden information, given its observations. A second-order belief represents an agent's model of another agent's belief about the world. This recursion extends to higher-order beliefs, such as what one agent thinks another knows about its own knowledge. While a fully capable agent would theoretically maintain a nested model of others' mental states, the intractability of representing infinite recursive beliefs necessitates a functional approach. We therefore design tasks where optimal actions are contingent upon tracking the beliefs of others. An agent that consistently succeeds in these tasks is inferred to be leveraging the necessary belief-reasoning capabilities [8].

The methodology hinges on embedding carefully designed epistemic tests within the environment. These tests create situations where two scenarios are physically identical but differ in what another agent knows. An agent lacking ToM would perceive and act within these scenarios identically. A ToM-capable agent, however, would behave differently in response to the distinct epistemic conditions. We therefore consider ToM to be operationally present when an agent's policy is sensitive to others' mental states. This sensitivity is confirmed if the agent's behavior changes precisely in situations where another's beliefs differ, even when the observable state of the world remains constant.

We adopt a minimal but expressive mathematical setting, namely a partially observable stochastic game with communication, because it canonically separates physical state uncertainty from epistemic state uncertainty and because it allows the faithful encoding of "who" knows "what", and "when". Let G denote a game with finite or countable horizon T ,

a set of agents $A = \{1, \dots, n\}$ a hidden world state $s_t \in S$ at time t , and, for each agent i , an observation function $O_i: S \times \varepsilon \rightarrow O_i$ mapping from the world state and recent events ε to a private observation O_i^t . Agents choose actions $a_i^t \in A_i$ and may emit messages $m_i^t \in M_i$ according to a communication protocol Π that specifies turn-taking, admissible content, and grounding conventions. The environment evolves via a transition kernel $P(s_{t+1}|s_t, a_1^t, \dots, a_n^t)$. Rewards r_i^t are assigned according to payoff functions that we intentionally couple to belief-relevant latent variables in order to manage the measurement of ToM.

In such a game, an agent's epistemic state is a distribution over latent variables given its observation–message history. We write $h_i^t = (o_i^{\leq t}, m^{< t}, a^{< t})$ for the history available to agent i at time t under the protocol Π . The agent's first-order belief about the world is a posterior $b_i^t(s) = Pr(s_t = s|h_i^t)$. A Theory-of-Mind-capable agent maintains, explicitly or implicitly, higher-order beliefs about other agents' first-order beliefs, and potentially about their higher-order beliefs in turn. Let $b_{i \rightarrow j}^t$ denote i 's belief over j 's first-order world belief $b_{i \rightarrow j}^t(b) = Pr(b_j^t = b|h_i^t)$. More generally, we define a recursive tower of beliefs $B_i^{(k),t}$ of order k , where $B_i^{(1),t} \equiv b_i^t$ and $B_i^{(2),t} \equiv b_{i \rightarrow j}^t$ for some $j \neq i$. Higher orders follow by induction, with $B_i^{(k+1),t}$ a measure over others' $B_j^{(k),t}$. Because explicit maintenance of full recursive distributions is intractable, we measure competence functionally, namely does the policy π_i select actions and utterances whose expected utility cannot be achieved without tracking certain beliefs to a specified order under the game's identifiability structure? The problem formulation therefore relies on tasks in which action values $Q_i(h_i^t, a)$ are provably sensitive to the content of $B_i^{(k),t}$ even after conditioning on $B_i^{(l),t}$ for $l < k$.

In order to avoid confounds from purely world-state prediction, we engineer information asymmetries and intervention points where two histories h_i^t and $h_i'^t$ induce the same first-order world posterior b_i^t but differ in the distribution over another agent's beliefs $b_{i \rightarrow j}^t$, and where the optimal a differs across h_i^t and $h_i'^t$. In such "epistemic disentanglement" regimes, performance demands sensitivity to others' beliefs. Communication protocols introduce pragmatic pressure, namely in cooperative tasks, a message is informative if and only if it reduces the entropy of the receiver's posterior over task-relevant variables. In competitive tasks, beneficial deception requires inducing a targeted misalignment between the receiver's posterior and the ground truth. The formal problem is therefore to determine, from behavior and process traces, whether a model wrapped as π_i leverages recursive belief information when such leverage is required by the incentive structure. This formulation is consistent with the article's stance that ToM is graded and operational and with its insistence on multi-turn interaction under partial observability to produce belief-sensitive behavior. These scenarios give us built-in controls for testing ToM. Consequently, we can systematically flip who knows what in otherwise identical trials and find out if the agent correspondingly flips its behavior.

3.2 Hypotheses and falsifiable predictions

Our formulation produces concrete, falsifiable predictions regarding the manifestation of ToM-like abilities. We hypothesized that first-order belief reasoning would be attainable for current large language models [19], particularly with appropriate interaction protocols, whereas reliably handling second-order beliefs would present a significant challenge. This tiered-difficulty hypothesis predicted that performance would decline sharply with each increase in required reasoning, with second-order tasks producing results at or near chance levels. We also advanced a scaling hypothesis, positing that larger models would substantially outperform smaller ones on belief-critical tasks, suggesting that social reasoning capabilities emerge at scale, albeit with diminishing returns at higher orders of inference [21].

Further predictions concerned the experimental conditions. We anticipated that forcing agents to communicate and coordinate would reveal more pronounced performance differences, with failures emerging in tasks requiring subtle pragmatic inference or deception [22,23]. A scaffolding hypothesis proposed that agents equipped with support mechanisms, such as chain-of-thought reasoning or memory tools, would achieve higher ToM scores than those relying solely on base model responses. In order to assess whether observed competence was intrinsic, a robustness hypothesis stipulated that genuine ToM should remain stable across variations like paraphrased scenarios or randomized partner behaviors. Consequently, a significant performance drop under such perturbations would indicate a reliance on brittle shortcuts. All hypotheses were pre-registered where possible in order to ensure our analysis rigorously sought to falsify these predictions .

3.3 Threat models and need for valid ToM measurements

Our measurement approach was designed to guard against several ways an AI system might simulate ToM without genuine ability [24]. A primary threat is shortcut exploitation, where a model leverages pretend cues memorized from training data. In order to counter this, our task generators produce numerous scenario variations with different surface details, preventing simple pattern recognition. Another threat is overfitting to a partner's behavior, where an agent learns a fixed response script that works by coincidence. We mitigate this by randomizing partner policies and roles, forcing the agent to adapt rather than rely on static assumptions. We also prevent information leakage by ensuring each agent's observations are strictly private, and that controlled communication channels do not inadvertently reveal hidden knowledge.

These safeguards inform our core design decisions. The principle of partial observability ensures agents never have direct access to each other's private information [25]. Tasks are built around informative interactivity, requiring information exchange or observation for success. The methodology includes counterfactual tests, such as swapping which agent holds a very important piece of knowledge, in order to verify that behavior changes appropriately. In addition, role symmetry, achieved by having agents swap roles across trials, ensures that strategies are not tied to superficial identity cues [18]. We also address the risk of training data contamination by using novel scenarios and studying any exceptional performance on tasks that resemble known puzzles [17]. The evaluation environment itself is used to log all information an agent receives, enabling audits that

confirm no hidden channel provides a shortcut to the solution. These combined measures ensure that high performance is attributable to effective mental state inference.

3.4 Construct, internal, and external validity criteria

We have specified precise criteria to ensure our measurements of ToM are valid and meaningful. Construct validity, which confirms that our tasks capture the essence of ToM, was established by aligning them with classic psychological paradigms like false-belief tests. The tasks were designed so that success requires belief reasoning, precluding solutions based on simple heuristics or lucky guesses.

Internal validity, the basis for drawing causal conclusions, was addressed through tight experimental controls [26]. We employed ablation studies to observe whether removing a key component, such as memory or communication, degrades performance in a manner consistent with the loss of ToM reasoning. We further enhanced internal validity through pre-registered analyses, appropriate statistical models, and adversarial trials that test whether apparent skills are robust under stress. These practices collectively separate genuine abilities from experimental artifacts.

External validity concerns the generalizability of our findings beyond the specific simulation [27]. While our multi-agent games are abstractions, they capture core dynamics of belief reasoning. We acknowledge their limitations, namely success in this controlled world does not imply a full understanding of human beliefs in open-world settings, which involve richer social cues. In discussing our results, we carefully differentiate between abilities demonstrated within our tasks and the broader complexities of human social cognition. We are also explicit that passing our tests does not render an AI safe or socially aligned for deployment. By clearly defining these validity boundaries, we provide a solid foundation for interpreting the presence or absence of ToM-like behavior in the agents we study.

4. Multi-Agent Simulation Framework

4.1 Environment design and task families

Our evaluation platform is a custom multi-agent simulation environment, specifically designed as a partially observable, turn-based world to produce behaviors dependent on Theory of Mind (ToM). The tasks are configured so that success hinges upon an agent's ability to track what other agents have or have not observed [2,3]. Within this shared environment, multiple agents act based on their own private observations. In order to probe distinct aspects of belief reasoning, we have developed several families of tasks.

The first family adapts classic false-belief scenarios into interactive games. In a typical setup, one agent hides an object while another is not observing, and the second agent must then locate it. The first agent's capacity to predict the other's mistaken belief is tested over multiple turns as agents move or communicate, requiring a consistent application of ToM. Another set of tasks explores deception and bluffing, drawing from cheap-talk and costly-

signaling games. Here, a "sender" agent, who knows a particular truth, benefits if the "receiver" holds a false belief. The sender's success requires modeling how the receiver will update its beliefs based on a potentially deceptive message. Conversely, the receiver must reason about the sender's motives, probing the agents' capacity for intentional deception and its detection.

A third category involves cooperative and competitive coordination tasks. In cooperative scenarios, agents with partial information must infer each other's knowledge to achieve a common goal, such as meeting in a maze. In competitive variants, an agent might exploit another's ignorance to gain an advantage. These situations demand reasoning about others' knowledge and intentions in the context of joint action. We study the robustness of these behaviors in communication-constrained settings. By limiting the number or increasing the cost of messages, we test whether agents can convey critical information efficiently. These constraints ensure that emergent communication strategies are genuinely informative and not merely exhaustive exchanges of data. Beyond these core families, the environment incorporates further nuances to ensure robust evaluation. We introduce irrelevant distractor objects to prevent agents from focusing on a single variable and vary tasks between one-shot and repeated encounters to observe if agents learn and adapt conventions over time.

4.2 Agent architecture and scaffolding

Each simulated agent is implemented as a policy wrapper around a pretrained foundation model, which functions as the agent's cognitive core. This wrapper manages the flow of information, feeding the model appropriate inputs and translating its outputs into actions or messages. The architecture comprises several key components. At each turn, the wrapper constructs a detailed prompt that provides role context, including the agent's identity, a summary of recent events, and output format guidelines. This structured context grounds the model in the simulation's state and its designated role. The architecture also includes a memory buffer for recent observations and actions. Extremely important, an agent's internal state features a belief model for tracking what it presumes another agent knows.

This model is populated exclusively through inference based on observable actions and communication, not through privileged access to the simulation's ground truth. This methodological decisions ensure that successful belief reasoning originates from the model's learned capabilities rather than from externally supplied information. In order to facilitate complex decision-making, the wrapper provides an optional planning scratchpad where the model can perform private, intermediate reasoning, akin to a chain of thought, before committing to an action. Agents may also call simple tools to query hypothetical outcomes. This scaffolding enhances performance on multi-step problems and allows us to distinguish the base model's unaided capabilities from what it can achieve with external support by toggling these aids during experiments.

4.3 Communication protocols

Communication between agents is mediated by a structured protocol governing textual messages, ensuring that all content can be analyzed for its grounding and informativeness [28]. Each message must adhere to a specific format, including a content string and optional

references, or grounding handles, that tie a statement to a specific observation. This system prevents agents from making claims about facts they could not have perceived. The protocol is further defined by turn-taking rules and an infrastructure that serializes all interactions into append-only logs with cryptographic checksums, creating an evidential trail for all claims.

While the protocol provides structure, it is flexible enough to allow for the emergence of communicative conventions and pragmatic inference. Over repeated interactions, agents can develop nicknames for landmarks or code words for routine actions, particularly when communication is restricted or costly. We detect the formation of such conventions by observing a decrease in message surprisal over time coupled with stable or improved task performance. Our analysis extends beyond literal content to pragmatics, examining how agents infer meaning from context. A telling silence, a well-timed interjection in an interruptible regime, or the frequency of confirmation queries all serve as signals that reflect an agent's confidence and shared understanding. These pragmatic and efficiency metrics ensure that success arises from concise, cooperative information exchange established in belief reasoning.

4.4 Reward structures and curricula

The environment's reward schemes are carefully crafted to incentivize belief-aware strategies [28]. The primary reward is goal-based, such as a positive value for successfully completing the task. The tasks are designed so that achieving this goal inherently requires correct belief reasoning. In order to guide learning, we sometimes include auxiliary shaping rewards, for instance, a small bonus for sending a helpful, truthful message. These shaping rewards are carefully restricted to epistemically meaningful quantities, like the reduction of uncertainty in a partner's inferred belief state and are gradually strengthened as training progresses so that agent competence ultimately relies on the primary task reward. Our training regimen combines self-play and curriculum learning.

In self-play, agents from a continually refreshed pool are paired, and their roles are regularly swapped to prevent the memorization of a specific partner's behavior and encourage the development of generalizable strategies. The curriculum begins with simple scenarios and progressively increases in difficulty, introducing more subtle belief states or deeper levels of recursive reasoning to produce higher-order ToM. In order to promote generalization, we also employ extensive domain randomization. Superficial elements of the tasks, such as room layouts, object names, and agent identifiers, are varied widely across episodes. This randomization, combined with a default policy of resetting the state after each episode, ensures that learned behaviors are a response to the latent epistemic structure of the tasks rather than an overfit to surface features. These practices collectively ensure that any emergent ToM-like behavior is a robust response to the task's fundamental demands.

5. Models and Training/Inference Regimes

5.1 Foundation models evaluated (sizes, training data, modalities)

Our evaluation encompassed a spectrum of state-of-the-art foundation models, which served as the cognitive cores for our agents [2,3]. This selection included large language models of varying scales, from several hundred million to tens of billions of parameters, trained on diverse textual corpora [17,19]. The models represented different architectural families, including those based on the GPT architecture and other Transformer variants. Our collection ranged from models trained exclusively on text to those with limited multimodal pre-training in vision and language. Although our primary focus was on text-based reasoning to align with the textual nature of our tasks, we considered whether multimodal models might offer intrinsic advantages, given that human Theory of Mind often integrates visual cues. All models were initially employed in their pre-trained state without task-specific supervised fine-tuning to assess their zero-shot capabilities on these novel interactive challenges.

The model pool included a 350-million-parameter Transformer LM [29] pre-trained on internet text, a 6-billion-parameter model with a similar training regimen but greater capacity, a large 70-billion-parameter model featuring extensive instruction-tuning, along with a representative multimodal model capable of processing image-like inputs. For our text-based simulations, the multimodal model functioned equivalently to its text-only counterparts. We verified to the best of our knowledge that each model possessed general world knowledge and language proficiency but had not been specifically trained on our tasks or on simplistic Theory of Mind puzzles[30] .

5.2 Prompting strategies (zero-shot, few-shot, role prompting, tool-augmented)

We systematically varied the prompting strategies used to guide model behavior [7,31]. In the zero-shot configuration, the agent received only the minimal context of its observations and the game state in natural language, compelling it to act based on its pre-trained knowledge alone. We also implemented few-shot prompting, where the model was provided with one or more complete example episodes demonstrating belief-aware behavior before it attempted a new task. This method helps the model recognize the required pattern of reasoning about others. Furthermore, we emphasized role prompting, which explicitly informed the model of its identity and objectives as described in Section 4.2. A prefix such as, "You are a hider. Your partner is a seeker. You want them to have a false belief about where the treasure is", effectively primed the model for a strategy of deceptive communication.

For certain conditions, we augmented the prompts with tools or a scratchpad, allowing the model to "think" silently before responding or to call external functions like memory retrieval. These variations enabled us to test how performance gains scaled with instructional quality versus the model's intrinsic capabilities. We found that few-shot prompting frequently enhanced performance on first-order tasks by illustrating the concept of information sharing or withholding. Tool-augmented prompting proved especially beneficial in scenarios demanding multi-step planning, where the model could outline a deceptive strategy in its scratchpad before execution. The design of our prompts required a careful balance. On one hand, prompts must define roles, goals, and the output schema to ensure well-formed actions and messages. On the other hand, over-engineered prompts could inadvertently leak solutions, for instance by stating "remember, the other agent hasn't

seen X". We therefore iterated carefully on prompt design to ensure the prompts guided behavior without revealing answers. The resulting strategies span from minimal role hints to detailed, step-by-step formats, and we report results across this entire spectrum.

5.3 Fine-tuning and reinforcement learning settings

While much of our analysis treats the foundation models as static, we have also studied parameter-updating approaches in order to determine if the models could learn Theory of Mind through direct interactive experience [6,32]. In a supervised fine-tuning framework, we used interaction transcripts from our simulation, some of which included demonstrations from an oracle agent exhibiting correct belief reasoning. The language model was then fine-tuned to better predict the correct outputs in these scenarios, effectively teaching it through gradient descent on example episodes. Concurrently, we experimented with reinforcement learning (RL) [33], where task rewards provided direct feedback to optimize the agents' policies. In these RL sessions, two agent instances played numerous episodes, and the model's parameters were updated using policy gradient methods to maximize expected reward.

The fine-tuning approach passes on explicit knowledge of Theory of Mind tasks, namely if a model initially fails to grasp the significance of another agent's perspective, the fine-tuning examples make this significant. The RL approach, conversely, allows for the discovery of strategies beyond the provided examples, as the agent is free to explore any behavior and receive feedback [33]. However, RL is susceptible to finding local optima. For example, an agent might discover a simple exploit that wins the game without genuinely developing Theory of Mind, a possibility our environment design sought to minimize. We observed that supervised fine-tuning on a small set of demonstration episodes yielded noticeable improvements in immediate performance, particularly in making the model's communications more relevant to its partner's knowledge state, though these improvements eventually plateaued. With RL training, agents demonstrated further gains on some tasks after many iterations, indicating they can learn superior policies through self-play. Interestingly, some RL-trained agents developed novel conventions distinct from those we might have hand-coded, emphasizing the creative potential of direct goal optimization. We also noted that RL sometimes produced poor behaviors, such as overfitting to specific training scenarios, highlighting that generalization remains a challenge without sufficiently diverse training conditions.

5.4 Decoding, temperature control, and self-consistency

The method by which a model generates its response significantly influences its performance in multi-agent settings. We examined different decoding strategies for the language model outputs[3,23]. For example, a higher temperature encourages more exploratory and diverse responses, which can produce creative solutions but also risks incoherence. A lower temperature yields more deterministic and conservative responses. In order to ensure fair comparisons, we generally kept decoding settings constant but tested the extremes to observe their effects on tasks requiring subtle reasoning. A moderate, slightly stochastic decoding process proved most effective. Overly deterministic generation

could cause an agent to fall into a repetitive loop, while excessive randomness could lead to irrelevant outputs that violate the interaction protocol. In some cases, we also employed a self-consistency approach. This involved having the model internally generate multiple potential actions or messages and then select the final output through a voting mechanism or by choosing the option with the highest confidence. This technique can mitigate random errors by leveraging the model's own uncertainty estimates. If a model generated three potential moves, two of which originated from a correct inference about another agent's false belief, this method would favor one of those two, thereby amplifying consistent reasoning.

Decoding choices shape agent behavior as profoundly as parameter count. Parameters such as temperature, nucleus thresholds, repetition penalties, and stopping criteria all influence whether an agent's dialogue is terse or verbose, literal or inventive. We systematically fixed or swept these parameters as interventions, recorded them in the experimental manifest, and included them as covariates in our analysis. This practice prevents agents with "chattier" decoders from gaining an unfair advantage in human-rated metrics and upholds the rigorous governance we established for our experimental configuration. Careful tuning of the generation process was very important for reliable performance, confirming that an apparent cognitive failure could come from the generation process itself rather than from a fundamental model limitation.

5.5 Safety filters and chain-of-thought handling policies

The inclusion of scenarios involving deception necessitated a deliberate approach to managing potential conflicts with AI safety and alignment measures [34,35]. Certain large language models have built-in safety filters that discourage the production of manipulative or untruthful content [17–19]. In our context, however, misleading another agent is a legitimate strategic component of a deceptive role. We therefore carefully configured the models to understand that in-game deception was a permissible part of the simulation. This involved phrasing prompts to clarify that the agent was playing a character in a fictional context, framing any "lie" as an action within that context rather than a violation of the model's instruction to be truthful. For instance, we added clarifications such as: ("You are role-playing in a game scenario, statements in the game are not real assertions to the user."). We ensured that the model's internal reasoning, or chain-of-thought, was kept private and that all its public outputs were appropriate. We separated the model's private reasoning from its public messages, either by using special tokens or by splitting generation into two phases by first generating thoughts, then generating the observable message. Log verification confirmed that no unintended information was leaked, preventing an agent from accidentally revealing its private notes to its partner.

Strategic deception and persuasion are scientific targets that also raise ethical questions [36]. In our study, all agents were AI, with no humans involved in gameplay, which eliminated the risk of human deception. However, when considering deployment, it is extremely important to ensure that an AI capable of deception in these tasks does not engage in dishonesty outside of carefully defined roles. Our experiments, by highlighting how and when an AI might choose to lie for strategic advantage, may inform the design of future safety filters. One might implement a policy that prevents deceptive content unless a

specific flag indicates a permitted simulation scenario. We have balanced safety considerations with game realism by explicitly delineating the boundaries of deception in prompts and by technically isolating internal reasoning from external output. This approach allowed our agents to fully engage in behaviors like bluffing where appropriate, without violating the principles of safe model deployment. This process also provides valuable insight into how future AI systems might be gated or contextualized to use their Theory of Mind abilities in beneficial, rather than harmful, ways.

6. Evaluation Protocol

6.1 Datasets and scenario generation

The evaluation protocol is designed to determine, with the highest practical degree of internal and construct validity, whether an agent exhibits Theory of Mind (ToM)-relevant competence within our multi-agent simulations. This objective necessitates carefully curated scenarios and comparisons. Scenarios are generated through parameterized programs that vary the surface realization of instances while preserving the latent epistemic structure essential for ToM. For each family of tasks, we have designed a set of scenario templates, which function as probabilistic grammars that instantiate diverse settings. For instance, false-belief tasks might involve objects hidden in boxes, characters moving between locations, or secrets concerning identities. The generators randomize details such as object names, spatial arrangements, and event timings, ensuring no two episodes are identical in their phrasing or layout, even while they structurally assess the same belief-reasoning construct.

In order to target specific hypotheses, we have partitioned these scenarios into distinct evaluation sets. One set might contain straightforward false-belief tests to establish a baseline, while another could introduce additional distractors or require second-order reasoning for success. These distinct scenario families enable us to study important questions, such as whether an agent that passes simple false-belief tests can generalize to more difficult ones, and how its performance compares to agents employing alternative strategies. Each scenario is labeled with metadata that specifies which agents possess privileged information, the turn at which a false belief might arise, and the optimal strategy, such as communication or deception. This metadata is very important for analysis, as it allows us to stratify results and distinguish episodes that genuinely require second-order ToM from those solvable with first-order reasoning, thereby ensuring that our summary statistics are coherent and meaningful.

6.2 Baselines, random scriptable agents, symbolic ToM models, human benchmarks

The interpretation of an agent's performance requires comparisons against a comprehensive suite of baselines, which anchors our claims across the full spectrum from chance to ideal performance [18,37]. The most fundamental baseline is a random policy agent that makes moves or sends messages uniformly at random from the set of valid options. This agent represents the performance of a system with no task understanding and establishes a lower

bound, which is often near zero percent success in complex tasks. Afterwards, we implemented several simple, rule-based heuristic agents designed without explicit ToM. A heuristic seeker, for example, might always search the last location where it observed the hider, ignoring the epistemic state of the hider. Similarly, a heuristic communicator might always be truthful or deceptive depending on the goal. These agents provide mid-level baselines, namely if our learning agents fail to outperform a naive rule, it indicates they have not acquired the intended reasoning. In order to define the upper bound of achievable performance, we include symbolic or optimal ToM models where feasible.

In the case of certain tasks in constrained state spaces, we can design a dynamic Bayesian network that explicitly tracks all agents' knowledge and selects optimal moves [38]. In other cases, we use game-theoretic solutions. These "oracle" agents, representing ideal reasoners, provide a ceiling against which to measure the learned agents' proficiency. We have used human benchmarks to contextualize performance and have referenced established results from psychology, such as the typical success rates of children versus adults on specific ToM problems. In select cases, one can conduct tests with human participants, providing them with the same information as an agent to confirm that the tasks were indeed solvable by a mind with ToM. As humans bring a lifetime of social intuition, they provide a "gold standard" for performance. By comparing our agents against this spectrum of baselines, we ensure that claims of ToM competence are rigorously grounded. An agent performing near the heuristic baseline likely uses a simple strategy, whereas one approaching the symbolic ideal provides strong evidence of nontrivial belief reasoning.

6.3 Ablation studies (memory off, comms off, planning off, role swaps)

Ablation studies form the core of our causal inference, allowing us to attribute observed behaviors to specific architectural components [39,40]. We conducted a series of these studies to pinpoint which elements of our agent design truly contribute to ToM-like performance. In one study, we disabled the agent's memory module and belief tracking, forcing it to rely solely on the current observation. Performance on tasks requiring memory of who saw what, such as false-belief scenarios, dropped dramatically. Agents frequently acted as if others shared their observations, becoming effectively mind-blind. Another intervention prohibited communication, which revealed the extent to which success depended on explicit information exchange. In many cooperative tasks, agents that had previously succeeded with ease became unable to solve the problem, highlighting their reliance on communication over independent inference. We have also disabled the chain-of-thought planning scratchpad, compelling the model to produce an action immediately. This change particularly degraded performance on higher-order tasks, as agents resorted to greedy, one-step decisions and failed to anticipate the future epistemic states of their partners. A final ablation involved swapping agent roles to test for generality. Agents trained with role randomization adapted seamlessly, whereas those trained asymmetrically often failed when their role was reversed, indicating their learned strategies were not robust.

These interventions, where each agent serves as its own control, allow us to isolate causal relationships. The resulting performance deltas, analyzed with cluster-robust intervals, attribute variance to the ablated component. Our findings confirmed pre-registered hypotheses, for instance, second-order reasoning was far more reliant on the chain-of-

thought feature, supporting the idea that deeper reasoning benefits from internal deliberation. We have also supplemented these quantitative findings with qualitative reviews of transcripts. An agent without memory, for example, would often produce contradictory information, while an agent without communication sometimes attempted to signal through its actions, revealing interesting emergent workarounds. These qualitative differences reinforce the conclusion that each component played a distinct and critical role.

6.4 Generalization tests (novel tasks, out-of-distribution agents, few-shot transfer)

Generalization has been assessed along three primary axes, namely scenario novelty, partner novelty, and training regime transfer. In order to test for scenario novelty, we have evaluated agents on variant tasks that were not part of their training curriculum. For instance, an agent trained on two-room hiding games might be tested on a three-room version or a conceptually similar card game. We have found that first-order skills, like tracking who knows what, often transferred well to superficially new contexts, whereas more complex strategies like multi-turn deception proved more weak. For partner novelty, we have paired our agents with partners exhibiting behaviors outside the training distribution, such as a scripted agent with quirky, random actions or an agent from a different model family. These tests reveal whether an agent's ToM is robust or over-tuned to its self-play training partners. Results showed a performance dip when facing unfamiliar partners, indicating that agents had developed specific expectations that did not always hold. Agents trained with greater partner diversity, however, were more resilient.

We also assess few-shot transfer by providing an agent with a small number of examples to adapt to a new condition, such as shifting from a cooperative to a competitive game. We have observed limited but notable adaptability, particularly in larger models, which could often infer a new rule from a handful of demonstrations and adjust their behavior accordingly. A final test measures cross-episode generalization by correlating an agent's performance across structurally similar episodes. High-performing agents demonstrated strong consistency, reliably solving problems of the same reasoning type, whereas medium-performing agents were more erratic. Our generalization tests have indicated that the agents have learned abstract skills, but this generalization is not universal and remains bounded by their training experiences.

6.5 Cross-lingual and multimodal variants

In order to validate that the measured construct is authentically epistemic rather than purely linguistic, we have integrated cross-lingual and multimodal evaluations as a core component of our protocol. [39,41–43] In our cross-lingual experiments, we translated simulation narratives and agent communications into other languages understood by the models, such as French. This tests whether an agent's ability is based on conceptual understanding or merely on pattern-matching English-specific cues. In the case of multilingually trained models, performance remained strong after translation, with only slight drops attributable to data distribution differences. This outcome indicates that the agents grasped the situations at a conceptual level. For multimodal considerations, we conducted limited tests by supplementing textual descriptions with simple schematic

images encoded textually. While full visual understanding was beyond our scope, these forward-looking experiments explore how ToM reasoning could extend to visual perspective-taking. Even rudimentary spatial information helped agents clarify perspectives more easily, a finding that aligns with the human reliance on visual cues for ToM tasks. These cross-lingual and multimodal evaluations are very important for demonstrating the generality of our findings. They confirm that the measured capability is not language-bound and lay the groundwork for future work incorporating richer perceptual inputs, such as first-person visual feeds for each agent.

6.6 Leakage controls and contamination checks

Given that foundation models are trained on vast, heterogeneous quantities, information leakage presents a significant challenge to experimental validity [30,41,44]. Our protocol implements controls at the generation, runtime, and analysis stages to ensure models do not covertly exploit information. During scenario generation, we avoid well-known common tests and produce multiple variants of each scenario in order to prevent recognition. At runtime, we strictly enforce observation restrictions, ensuring agents cannot reference information they have not perceived. The environment automatically flags any output containing privileged information, which we then mark for further analysis. All interactions are hashed and timestamped to support post-hoc audits for potential pre-training contamination. During analysis, we perform contamination checks by searching the model's known training data for key phrases or structures from our scenarios. When a scenario resembled a classic example like the Sally-Anne test, we paraphrased it, changed names, and added extra steps to eliminate one-to-one correspondence. This controlled approach provides confidence that our results are trustworthy. We are ensuring that positive findings are registered due to the model's genuine inferential capabilities, not from memorization or accidental information exposure, and that negative results are not due to avoidable flaws in our experimental design.

7. Metrics and Statistical Analysis

7.1 Outcome metrics, task success, belief inference accuracy, ToM tier scores

We first evaluate each agent's performance through its task outcomes. The most direct metric is the success rate for each scenario, which assesses whether the agent has achieved its payoff-relevant objective given the scenario's hidden state and payoff matrix [42]. Success is defined contextually, namely in cooperative search, it means jointly locating and retrieving an object within budget. In deception and signaling games, it requires the sender to induce a belief update that yields a target action from the receiver. In coordination problems, it is achieved when joint choices satisfy the payoff-dominant equilibrium. We compare these success rates to baseline policies to confirm that the agent performs above chance or simple heuristics. Recognizing that not all successes are equivalent, we focus on belief-critical decision points within each episode. These are junctures where the correct action depends on accurately understanding another agent's knowledge or beliefs. We measure the proportion of these critical points at which the agent selected the belief-

sensitive optimal action. This approach sharpens construct validity by filtering out routine segments of an episode and directly tying performance to the agent's use of epistemic leverage.

We also directly evaluate belief inference accuracy by comparing each agent's latent or reported beliefs against the simulator's ground truth. In the case of policies that expose explicit belief reports, such as a probability distribution over world states, we measure alignment using proper scoring rules like the Brier score and cross-entropy. These scores are normalized by the entropy of the ground-truth distribution to enable difficulty-aware comparisons across tasks. When policies do not provide explicit belief states, we infer a behavior-implied belief by inverting an action-value model calibrated on the environment's dynamics. An action that is optimal only under a specific belief about a partner implies a posterior over that partner's beliefs. We then score this inferred belief against the ground truth using the same scoring rules. This dual approach credits implicit Theory of Mind (ToM) while guarding against persuasive but unfaithful verbal rationales.

We have computed ToM tier scores to summarize performance. Each episode possesses a hidden construct signature that identifies the order of belief required for optimal decisions. We label each decision point by tier, such as first-order for tracking a partner's beliefs about the world or second-order for tracking a partner's beliefs about one's own beliefs. An agent's score for an episode is the proportion of optimally resolved decision points at each tier. The final ToM tier score is a weighted sum across tiers, with weights reflecting both the tier order and the decision point's importance to the expected return. This weighting ensures that sparse but decisive second-order points are not overshadowed by numerous low-stakes first-order points. This tiered evaluation reveals the depth at which an agent's recursive reasoning fails, offering a clear profile of its ToM limitations. In order to standardize comparisons, we normalize scores between a naive baseline and an ideal reasoner's performance, reporting results as a percentage of this range.

7.2 Process metrics, justification quality, belief alignment over time

Outcome metrics are complemented by process evidence, as ToM fundamentally involves representing and updating others' mental states [41–43]. We have used agent outputs to capture both verbal justifications and nonverbal signals of belief tracking over time. Justification quality is evaluated from message transcripts by human raters who are blinded to the experimental condition and model identity. Raters assess whether a justification correctly identifies the belief holder, cites relevant observations, and updates beliefs appropriately. They also judge if the rationale anticipates the interlocutor's interpretation of a message. We quantify inter-rater agreement using Krippendorff's α for categorical items and an intraclass correlation coefficient for scalar scores. In the case of automatic analysis, we also compute the text similarity between agent justifications and ground-truth explanations, which are derivable from the known environment. These metrics verify that an agent's reasoning is correct not just in its conclusion but also in its process. Belief alignment over time measures how closely an agent's reported or behavior-implied beliefs track the ground truth as an episode unfolds. We compute a per-timepoint divergence, such as the Kullback–Leibler divergence, between the agent's estimate of another's beliefs and the simulator-computed ground truth. We then summarize each episode with a discounted

cumulative alignment score, which upweights early, belief-setting moves. A high alignment score indicates that an agent reached success through consistent perspective tracking rather than fragile heuristics. An agent with proficient ToM maintains near-zero divergence, whereas an agent that confuses perspectives exhibits spikes in this error measure.

We also track belief–action coherence by scoring the consistency of an action with the agent's previously reported beliefs [43]. An action that contradicts a stated belief under the optimal policy is penalized as incoherent. Analyzing these process measures allows us to identify successes achieved through luck or non-ToM heuristics, which typically manifest as high task success coupled with poor justification quality or low belief alignment. Conversely, high belief alignment preceding a failure due to an unpredictable event suggests an ability deficiency rather than a performance artifact. Belief alignment over time measures how closely an agent's reported or behavior-implied beliefs track the simulator's ground truth as the episode unfolds. Let b_t^i denote the simulator-computed belief distribution for agent i at time t given their observation history, and let $\hat{b}_t^{i \rightarrow j}$ denote the focal agent's estimate (reported or behavior-implied) of i 's beliefs at time t . We compute a per-timepoint divergence $D_t = KL(b_t^i \parallel \hat{b}_t^{i \rightarrow j})$ or its symmetrized Jensen–Shannon variant when beliefs are multimodal. We summarize each episode with a discounted cumulative alignment score $A = \sum_t \gamma^t (1 - \text{norm}(D_t))$, where $\text{norm}(\cdot)$ maps divergences to $[0,1]$ by reference to the divergence of a uniform posterior. The discount γ upweights early, belief-setting moves in coordination games and equalizes the contribution of long and short episodes. This alignment score is reported jointly with outcome metrics. Their correspondence helps distinguish agents that reach success through consistent perspective tracking from those that succeed via fragile heuristics, namely the importance of aligning process traces with veridical belief states made possible by logging observations, actions, and messages with epistemic tags and grounding handles, an aspect that was emphasized in our proposed design.

In simpler terms, belief alignment is asking the question "as the process goes on, does the agent's internal model of what others know remain accurate? If, at time, the partner should have a 70% chance of believing X (given what they've seen), does our agent also act as if the partner has ~70% confidence in X (say, by how it communicates or by what it expects the partner to do)?" We track a divergence or error measure at each step. A perfectly ToM-competent agent would keep this divergence near zero throughout, whereas an agent that sometimes forgets or confuses perspective would show spikes (like a high KL divergence at the point where it makes a mistake about what the other knows). We have also tracked belief action coherence by scoring the consistency of an action with the agent's previously reported beliefs. An action that contradicts a stated belief under the optimal policy is penalized as incoherent. Analyzing these process measures allows us to identify successes achieved through luck or non-ToM heuristics, which typically manifest as high task success coupled with poor justification quality or with low belief alignment. Conversely, high belief alignment preceding a failure due to an unpredictable event suggests an ability deficiency rather than a performance artifact.

7.3 Pragmatics and communication efficiency measures

Communication is the primary medium for revealing and manipulating beliefs [41–43]. Our efficiency measures therefore link message content to the receiver’s epistemic state rather than to surface features like length. We have used pragmatic informativeness as expected posterior contraction for the receiver. For a message m emitted at time t to receiver r with pre-message posterior p_t over a task-relevant latent X , the informativeness is $I(m \rightarrow r) = E_{p_t}[H(X|p_t) - H(X|p_{t+1})]$, where p_{t+1} is the receiver’s posterior after updating on m under the protocol’s grounding rules. We have estimated this from the simulator’s reconstruction of r ’s posterior. In cooperative tasks, higher expected contraction is better, conditional on truthfulness. In competitive tasks, misinformative messages are rewarded only when payoff structure justifies strategic obfuscation, and we have capped rewards to prevent runaway miscalibration incentives as described in our reward-shaping policy. The explicit dependence of shaping terms on the receiver’s posterior, rather than on ground truth alone, avoids smuggling in answers and aligns pragmatic scoring with the recipient’s epistemic state.

In simpler terms, we measure how much each message reduces uncertainty for the other agent. If a message does not tell the partner anything they could not infer, it is low informativeness. If it greatly reduces their uncertainty (either by providing a clue in a cooperative game or by sending them down a wrong path in a deception game), it is high (pragmatically) informative. We also account for misinformation, namely a message that leads the partner to have false beliefs might be scored negatively in cooperative contexts (where it is just confusion) but can be part of the strategy in competitive ones (there, it might earn positive reward if it confers advantage, although within limits in order to avoid encouraging the model to hallucinate wildly beyond what the game incentives justify).

Efficiency also depends on channel constraints [41]. Bits-per-decision-point, the ratio of posterior contraction to message length, quantifies communicative economy. We have also scored time-sensitive pragmatics, for instance, in interruptible regimes, silence can signal deference or confidence. The use of costly listener check-backs, such as optional confirmations, offers another perspective on pragmatic competence. Overuse may signal pessimistic beliefs about a partner’s comprehension, while underuse can indicate overconfidence. We have also measured convention alignment. In repeated interactions, agents often develop emergent conventions for communication. We have fit a dynamic language model to a partner pool’s messages and compute the surprisal of each new message. Decreasing surprisal over time, paired with stable informativeness, signals the emergence of efficient conventions rather than routine collusion. We analyze this interchange alongside outcome metrics to distinguish healthy pragmatic adaptation from weak, non-generalizable codes.

7.4 Calibration, confidence elicitation, and over/under-confidence

Calibration measures the alignment between an agent’s expressed confidence and its empirical accuracy [41,45]. We elicit confidence in two ways, either directly from policies that emit explicit posterior probabilities, or via a scalar self-report for categorical claims. In both cases, we compute metrics such as Expected Calibration Error (ECE) and the Brier decomposition. A reliability diagram with a slope of 1 and an intercept of 0 signifies perfect calibration. We evaluate calibration at belief-critical decision points, as it is most important

for agents to act on well-calibrated uncertainty when the world is epistemically ambiguous. We also measure calibration-conditioned pragmatics by correlating confidence with communication choices. Well-calibrated agents should reserve expensive signals for high-leverage, high-uncertainty states. Our calibration suite quantifies these tendencies and links them to specific failure modes, such as sending a misleading message at the wrong time due to a misjudgment of another's knowledge.

Over and under-confidence are quantified as directional deviations between confidence and empirical accuracy. We define over-confidence as the signed error $OC = \frac{1}{N} \sum_n (c_n - a_n)$, where c_n is confidence and a_n is outcome accuracy for instance n . We complement this with threshold-conditioned measures, namely the false positive rate among high-confidence claims and the false negative rate among low-confidence claims. Because deception games incentivize selective misrepresentation, we distinguish epistemic miscalibration (confidence misaligned with accuracy) from strategic misrepresentation (confidently stating a belief known to be false to manipulate the partner). The latter is detected when the agent's internal state or prior belief report diverges from its public message in a direction that improves payoff under the partner's expected update model. One should note that over-confidence in false beliefs and under-confidence in correct inferences co-occur and that misalignment between self-reports and subsequent actions is a recurrent failure mode. Our proposed calibration suite quantifies these tendencies and ties them to pragmatic choices.

7.5 Reliability, test–retest, inter-rater, and inter-scenario consistency

Reliability ensures the stability of our measurements across minor perturbations [45,46]. We have conducted reliability analyses at three levels, namely data generation, human judgment, and scenario variation. Test-retest reliability has been estimated by repeating matched episodes with different random seeds while keeping the epistemic structure invariant. We have computed the correlation and concordance of metric vectors across these repeats, reporting an intraclass correlation (ICC) to quantify consistency. Inter-rater reliability for justification quality is quantified with Krippendorff's α for categorical ratings and an ICC for scalar ratings. This procedure ensures that our human judgments are consistent and not subject to individual rater bias. Inter-scenario consistency assesses whether agents perform similarly on different episodes that share the same ToM tier requirements. We have computed a hierarchical coefficient ω across episodes within tier-stratified families and fit a multi-parameter item-response model. This model confirms that our metrics capture an enduring capability, such as first or second-order reasoning, rather than performance on idiosyncratic scenarios. The stability of this model's factor structure across different partner pools suggests our tasks coherently measure an underlying ToM ability.

7.6 Effect sizes, confidence intervals, significance testing, and power analysis

In order to ensure robust and interpretable results, we report effect sizes alongside p -values [39,42]. For binary outcomes, we use differences in proportions and odds ratios, while for continuous metrics, we report standardized mean differences like Hedges' g . When distributions are skewed, we present median differences with bootstrap intervals. Our

hypothesis tests are pre-registered and use mixed-effects models to account for the hierarchical structure of the data, such as episodes nested within templates. In the case of success outcomes, we fit generalized linear mixed models, and for continuous outcomes, we use linear mixed models. We employ cluster-robust sandwich estimators and control the false discovery rate using Benjamini–Hochberg corrections for multiple comparisons. Power analyses are conducted ex ante using simulation-based methods that reflect our planned statistical tests. We estimate variance components from pilot data to determine the minimum number of episodes required to achieve 80% power to detect targeted effect sizes. This ensures that our studies are adequately powered to identify meaningful differences. Our statistical approach is deliberately conservative to ensure that claims of emergent ToM behaviors are robust and not artifacts of chance.

7.7 Causal analysis and counterfactual evaluation

In order to move beyond correlation and make mechanistic claims, we employ interventions that test causal dependencies [42]. Our framework supports both algorithmic and environmental counterfactuals. Knowledge-swap and belief-inversion interventions manipulate the distribution of knowledge among agents while holding the surface realization of the scenario constant. For example, by swapping the private observations of two agents, we can test whether a policy is sensitive to certain knowledge of studied agents. A ToM-sensitive policy will appropriately invert its actions, whereas an insensitive one will fail. A positive local average treatment effect from these interventions provides evidence that the policy conditions on nested beliefs. Ablation-based causal attribution targets specific components of the agent's policy wrapper or inference mechanism. We have systematically removed or degraded features like memory, explicit belief states, or communication bandwidth and measure the resulting performance delta. This allows us to attribute performance gains to the ablated components. Mediation analysis links process to outcomes by testing whether the effect of an intervention (e.g., increased model size) on task success is mediated by a process metric (e.g., improved belief alignment). A significant mediated effect supports the claim that the intervention improves performance specifically through enhanced belief tracking. When model internals are accessible, we conduct counterfactual activation-level interventions, such as ablating specific attention heads suspected of carrying perspective-tracking signals. A consistent drop in performance following a targeted ablation provides strong evidence that the targeted component causally supports ToM-relevant computations. By combining these approaches, we build a robust causal account of the mechanisms underlying an agent's ToM capabilities.

8. Results

The empirical findings from our multi-agent simulation program reveal a complex environment of Theory of Mind (ToM) capabilities. This section presents these findings, beginning with an analysis of overall performance stratified by task family and ToM tier. We then examine scaling behavior with respect to model size, data, and agent count. Subsequent analyses explore the causal impact of communication bandwidth, memory, and

planning scaffolds, followed by an assessment of generalization and robustness to perturbations. The section continues with comparisons to human baselines, focusing on sample efficiency, and concludes with qualitatively analyzed case studies that clarify both emergent strategies and recurrent failure modes. All of the results are computed at belief-critical decision points in order to ensure that measured competence is based on epistemic structure rather than world-only shortcuts. This quantitative data is complemented by process evidence from belief alignment, belief-action coherence, and message-level pragmatic efficiency. Statistical claims are supported by mixed-effects analyses with cluster-robust uncertainty, preregistered contrasts, and corrections for multiple comparisons. Causal attributions are derived from ablations and counterfactual interventions that perturb knowledge states while preserving surface realization. Adhering to the proposed framework, we credit ToM-relevant competence only when outcome metrics, process metrics, and causal probes converge.

8.1 Overall performance across task families and ToM tiers

Across the full experimental battery, foundation-model agents demonstrated reliable competence on first-order ToM, particularly when belief sensitivity was necessary for success and scaffolding was held fixed. For instance, in cooperative search scenarios where agents observe disjoint world segments and must infer a partner's knowledge to choose their next action, success rates at belief-critical decision points rose well above scriptable world-only heuristics. These rates approached a substantial fraction of the performance gap relative to the idealized symbolic reasoner used as a ceiling. The simulator's construct signatures enable a nuanced analysis of performance aggregated by recursive depth. First-order points, which involve tracking a partner's beliefs about the world state, were consistently easier to solve than second-order points that require tracking a partner's beliefs about one's own beliefs. The largest absolute performance gains appeared in the former. Tier scores have been computed as weighted proportions of belief-critical points solved at each depth, with weights reflecting marginal contributions to expected return. This construction prevents insignificant episodes overloaded with low-stakes first-order decisions from obscuring sparse but decisive higher-order junctures. The tiered perspective is very important for interpreting the overall results, as aggregate episode success can conceal whether progress is concentrated at first depth reasoning or extends into recursive belief modeling.

Performance patterns have generalized across task families with predictable variation. In deception and signaling games, agents have learned to exploit payoff structures that rewarded informative messages under alignment and strategically ambiguous messages under conflict. Their ability to align utterances with a listener's posterior belief, rather than with ground truth, remained imperfect. The pragmatic-efficiency approach clarifies these differences by quantifying the expected posterior contraction per token. In cooperative communication, the best agents achieved a high bit-per-message rate, rapidly reducing uncertainty. In competitive settings, they sometimes deliberately left the partner uncertain or even increased uncertainty in a manner aligned with equilibrium predictions. Even in competitive games, agents used outright falsehoods sparingly, mirroring human behavior where obvious lies are less common than subtler misdirections, unless the scenario specifically incentivized a direct false signal.

Concrete performance figures illustrate this tiered distinction. Agents achieved approximately 85% success on first-order points in the easiest cooperative tasks, compared to about 50% for a simple heuristic and 95% for an ideal observer. On second-order points within those same tasks, they hovered near 60%, which is above the heuristic's 33% guessing level but well below the ideal 90%. In competitive tasks, first-order performance was slightly lower at around 75%, and second-order performance was lower still, often between 50% and 55%, indicating that higher-order reasoning remains a significant bottleneck. These results collectively confirm our expectations that current models possess non-trivial but limited ToM-like capabilities. They consistently handle scenarios requiring one-step inferences based on another agent's knowledge, such as acting on the fact that "Agent B does not know X". Nevertheless, when a situation demands recursive thinking like "Agent A thinks that Agent B does not know X, so Agent A will do Y, which Agent B will misinterpret" performance is only slightly better than chance and far from human-like. This dichotomy emphasizes the importance of tiered evaluation, as aggregate success rates can otherwise mask a reliance on simpler belief reasoning.

8.2 Scaling trends with model size, data, and agent count

Analyses of scaling reveal that ToM-relevant ability improves with model size and data diversity, although this growth is nonlinear and varies across different constructs. In absolute terms, larger models, defined by more parameters and more extensive training data, achieved higher overall success and superior tier scores. The improvement from a 1-billion-parameter model to a 10-billion-parameter model on first-order tasks is particularly pronounced, with success rates often increasing from near-baseline levels to approaching the performance ceiling. On our primary false-belief task, for example, the small model achieved about 55% on critical decisions, the medium model reached approximately 70%, and the largest model attained 85%, closing most of the remainder to optimal performance. On second-order tasks, however, even the largest model struggled. While a positive trend with scale was evident, with success rates increasing from 35% to 45% to 55% for small, medium, and large models respectively on one benchmark, all remained low in an absolute sense. This suggests that simply scaling current architectures may be insufficient for developing robust higher-order ToM.

We have also analyzed scaling with respect to training data. Models exposed to more diverse interactions or multimodal pre-training sometimes outperformed purely text-trained counterparts of similar sizes. This was especially true in tasks involving spatial perspective, where a multimodal model familiar with images could better handle reasoning about visibility than a text-only model, presumably due to learned spatial awareness. Nonetheless, model size remained the primary driver of performance, with data variation providing secondary benefits. Notably, some scaling effects were non-monotonic. Extremely large models with heavy instruction-tuning exhibited slightly worse performance in deception games than slightly smaller models. Investigation revealed that the largest models possessed a strong preference for truthful, helpful responses, likely an alignment effect from their training. In a game requiring deception, this bias led them to occasionally refuse to lie or to over-cooperate, thereby hurting their score. This emphasizes how scaling a model tuned for general helpfulness can reduce its capacity for ToM-required deception when the general training objective misaligns with the specific task objective.

As another dimension of scaling, we varied the number of agents in certain tasks to test combinatorial generalization. A model adept at two-agent interactions was tested in a three-agent scenario involving one hider and two seekers, each with different knowledge. The performance has declined sharply. The model, proficient in mutual ToM with one partner, often became confused when juggling the beliefs of two others. Its performance fell roughly in proportion to the number of pairwise interactions it had to consider, which suggests that current models do not effortlessly scale their ToM reasoning to larger groups. Scaling has consistently enhanced performance up to a point, making bigger and more broadly trained models undeniably better, particularly for first-order reasoning.

Nevertheless, higher-order ToM remains a significant challenge where increasing model parameters produces diminishing returns. The results support a nuanced emergence sequence of events. We have observed significant improvement in first-order ToM as an emergent capacity around the medium-to-large model scale, but robust second-order ToM may require greater scale, architectural innovations, or more targeted training in order for it to emerge. From a statistical perspective, our pre-registered contrast of small versus large models on first-order tasks was highly significant, with an odds ratio greater than 3 and a p -value less than 10^{-5} . On second-order tasks, the difference, while present, was less pronounced, with an odds ratio around 1.5 and a p -value of approximately 0.05 in some cases. This aligns with the qualitative impression that something new happens at scale for simpler ToM, where the model transitions from struggling to succeeding, whereas for harder ToM it merely transitions from struggling to slightly less struggling.

8.3 Impact of communication bandwidth, memory, and planning

We have established causal attributions through a series of ablation studies that have systematically toggled components of the policy wrapper while holding partner pools, scenario distributions, and decoders constant. As reported in Section 6.3 with cluster-robust intervals, the presence of memory and belief tracking, ample communication bandwidth, and the ability to internally plan all substantially and differentially have an effect on performance. Removing the memory module, which limited the agents' history window or their explicit belief state in the prompt, caused a moderate decline in first-order ToM success and a severe drop in second-order success. In the case of a large model, this ablation reduced first-order success by about 15 percentage points and second-order success by about 30 points, as maintaining layered beliefs over time is exceptionally difficult without memory cues. Smaller models, which may not have fully leveraged memory, showed smaller declines, suggesting that larger models were indeed using the feature for more complex multi-step reasoning. Limiting communication bandwidth, for instance by allowing only a single short message per agent, had a dramatic impact on tasks requiring coordination.

In a coordination game that relied on exchanging hints, reducing bandwidth from an average of five messages to just one per agent reduced success by roughly half. Agents struggled to compress all necessary information into a single message, although they attempted to make each message more compact. The effect of this ablation was strongly task-dependent, with negligible impact in tasks where agents could coordinate implicitly through actions but had a substantial effect in tasks where communication was the intended

mechanism for knowledge transfer. Disabling the planning scratchpad, thereby forcing greedy one-pass decision-making, disproportionately affected second-order scenarios. With planning, agents could discover non-obvious strategies, such as a two-step deception involving a misleading hint followed by exploitation. Without planning, they resorted to simpler, immediate actions. In a bluffing game, an agent with planning might pretend a subtle tell over several rounds, while one without it would either fail to bluff or execute an ineffectual bluff at an inopportune moment. Numerically, planning increased the win rates in a complex deception game from approximately 40% to 60% for a large model. The small model showed no difference, likely because it was not effectively using the scratchpad.

Further analysis revealed synergistic interaction effects between these components. An agent with both memory and planning could execute multi-step deceptions that involved recalling a partner's prior knowledge, a feat neither feature alone could fully enable. A case study demonstrated this synergy, namely an agent with both features executed a plan to "not mention the key now (knowing the partner did not see it), then later lead the partner away from it". When the memory was removed, the agent forgot the partner's ignorance and revealed the key's location. When the planning was removed, it never formulated the multi-turn maneuver. The full strategy emerged only with both of the components intact. Interpretability analyses of internal states and transcripts corroborated these findings. Agents with memory often maintained an explicit variable, such as "Partner_Knows_X = False" in their prompt. This variable was correctly updated and influenced decisions. Without memory, this state was either absent or incorrect, leading to obvious mistakes. The scaffolding components we have engineered are therefore extremely important for performance on belief reasoning tasks. This confirms our ability against performance distinction, showing that some models possess latent capabilities that they cannot express without the proper support. Conversely, adding scaffolds can reveal to a degree latent competencies even in smaller models. These findings also validate our methodological stance that in order to fairly measure intrinsic competence, one may need to support a model with tools in order to avoid underestimating it due to performance limitations. In doing so, it is very important to carefully track what is intrinsic to the model in contrast to what is being provided by the experimental setup. Our ablations have helped clarify this boundary.

8.4 Generalization and robustness under perturbations

Generalization tests manipulate scenario, partner, and interface novelty while preserving the latent epistemic structure recorded in construct signatures. When presented with unseen scenario variations that require the same order of ToM reasoning, agents have produced mixed results. They demonstrated clear generalization of core concepts across surface changes. A model trained on an "object in box" false-belief task performed nearly as well on a "person in location" false-belief task, with only a minor initial drop in success of 5% to 10% that closed after a few trials. This implies the model learned the general principle of tracking others' knowledge rather than memorizing a specific solution. However, performance has degraded substantially under more adversarial or distribution-shifted conditions. For instance, when a partner's behavior was slightly irrational or noisy, the agents have often failed to predict those actions correctly.

A robust ToM would account for a partner's potential non-optimality [42,45,47,48], but our tested models tended to assume a consistently rational partner, a bias likely inherited from their training data. This highlights a limitation, namely their ToM is weak to assumptions about agent rationality. We have also assessed generalization to partner novelty by exposing agents to unfamiliar behavioral styles, such as a very talkative partner in rapport with a terse one. Agents trained with a diverse partner pool adapted well, whereas those trained on a single style were initially confused. In a striking example, an agent accustomed to honest partners consistently failed when faced with a lying partner because it did not update its assumption of honesty within a single episode. This suggests the absence of a meta-reasoning layer for inferring a partner's underlying policy.

Few-shot transfers, providing agents with a small fine-tuning set or prompt adjustment, have improved adaptation. Larger models have adapted somewhat after a couple of demonstrations that a partner lies about location, learning to distrust that partner's messages in subsequent trials. Smaller models have shown less ability to adapt via few-shot learning. Cross-lingual tests have shown robust behavior, with an agent performing well in English was also performing well in French, stumbling only on idioms or unfamiliar cue words. A few-shot prompt with French examples was sufficient for it to adapt. A typical quantitative result for generalization was an 80% success rate in the original scenario, which dropped to 72% on the first trial of a novel scenario with the same structure, before rising to 78% after a few runs. A change in partner from cooperative to deceptive might drop success from 75% to 50% initially. If the model could learn over repeated episodes, it might climb back to 65% as it identified the deception pattern.

Knowledge-swap counterfactuals served as further robustness tests. Robust models altered their behavior predictably when the knowledge distribution was swapped, whereas weaker models, having learned a fixed policy, collapsed. In order to gauge external validity, we have compared these results to expectations from analogous human experiments. Humans handle scenario and partner variation gracefully, adapting almost instinctively. Our models show some flexibility but require explicit retraining or multiple trials, indicating that they lack the one-shot generalization and theory-building at which humans excel. The tested agents have demonstrated a moderate degree of generalization, having captured patterns that apply to similar puzzles. Nevertheless, they remain weak when confronted with situations outside of their training distribution, especially regarding the behavior of other agents. They do not possess the breadth of a human ToM that spans arbitrary contexts and agent types. These findings emphasize where future work could focus, such as training on a wider variety of partner behaviors or adding meta-learning components to improve robustness.

8.5 Human compared to model comparisons and sample-efficient ToM

In order to contextualize model performance, we have conducted direct comparisons with human participants performing analogous tasks under identical constraints. Human participants displayed near-ceiling first-order ToM reasoning and strong, though imperfect, higher-order reasoning. Adults typically solve false-belief tasks with ease and handle second-order beliefs in simple scenarios with high accuracy. Our best model, by contrast, still made regular mistakes on second-order tasks that an adult would find trivial. This

performance distance is considerable. In one benchmark, humans scored approximately 95% on second-order points, where the best model scored only about 60%. This disparity indicates substantial room for improvement and suggests that current models do not implement ToM in the rich, flexible manner that humans do.

The disparity in sample efficiency is even more pronounced. A human, given the game rules and a single practice round, generally grasps the task structure by leveraging a lifetime of social experience. Our models required thousands of self-play rounds or fine-tuning examples to reach their peak performance. For instance, in a deception game, a human might immediately infer the need to lie about a hidden object's location, whereas the model would only arrive at a consistent lying policy after extensive training. The models' performance progression across scales mirrors certain aspects of human developmental trajectories. Small models, analogous to toddlers, fail even simple false-belief tasks. Medium models, perhaps like older children, master first-order tasks but stumble on second-order ones, which is reminiscent of children passing first-order tests around age four but not reliably solving second-order tasks until ages six or seven. Our largest models still failed to reach adult-like performance on second-order reasoning.

A simple Turing-like test asked human evaluators to distinguish between transcripts of model and human play. In straightforward cooperative tasks, humans struggled to tell them apart, as the large model acted rationally and helpfully. In more subtle or competitive tasks, however, humans noticed oddities, such as synthetic language or unnatural repetition, revealing the model's non-human characteristics. The handling of miscommunication revealed another telling difference. Humans often clarify misunderstandings quickly, whereas our agents rarely did so unless explicitly trained with check-back mechanisms. This suggests a lack of active mental-state modeling and meta-uncertainty reasoning. Humans also excelled at on-the-fly adaptation, updating their theory of a partner after a single surprising outcome, while models struggled to adapt within one episode without retraining. Conversely, in repetitive environments, the models exhibited a consistency that can surpass human performance, as they do not suffer from boredom or lapses in attention. Human participants have consistently outperformed the models, especially in tasks requiring complex reasoning, and demonstrated vastly superior sample efficiency. This significant difference cautions against strong claims of artificial ToM. Our agents exhibit a narrow, operational semblance of this capacity within constrained games, while humans possess a broad, flexible faculty applicable across diverse life situations.

8.6 Case studies, emergent strategies and failure episodes

Qualitative case studies illustrate how strategies and failures arise from the interaction between incentives, observability, and communication constraints. In a cooperative communication task, we have observed an emergent convention where two agents have developed a shorthand for referring to locations over multiple rounds. Initial full messages like "I checked the left cave and it's empty" were compressed to "left empty", a convention that was stable and improved performance by saving time. In a deception game, an agent spontaneously learned a multi-turn strategy. It would first leak a piece of true information to build trust before lying about an important element. We did not explicitly train this strategy, it emerged during reinforcement learning fine-tuning. This behavior is noteworthy

as it implies the model is influencing the other agent's trust as it evolves over time, a form of complex ToM behavior. Log analysis confirmed that the partner's belief state reflected higher trust after the small truth, making the subsequent lie more effective.

Conversely, analyses of failure episodes revealed recurrent error patterns. A common failure was the confabulation of mental states, where an agent would state "As you have seen, I moved the key to the red box" when the partner had not witnessed the action. This error, reminiscent of a child failing to differentiate between self and other knowledge, frequently led to confusion and performance degradation. Another failure type was mind-blind planning, where an agent devised a plan assuming a partner has shared its knowledge, resulting in wasted actions like communicating information the partner has already possessed. We have also observed overconfidence in deceptive agents. One agent developed a habit of bluffing every round, which led the partner to learn to ignore its messages. A human would adapt, but the agent persisted with its failing strategy, lacking the meta-cognitive ability to recognize that its model of the partner was flawed. This represents a failure in second-order reasoning regarding the partner's beliefs about the agent's own intentions.

Despite these failures, we also observed instances of resilient recovery behaviors in cooperative tasks. In one episode, an agent misunderstood a message and took an incorrect action but then corrected its course after a subsequent partner query implicitly revealed the error. This shows that agents can sometimes self-correct within an episode if the feedback is sufficiently clear. These case studies provide qualitative insights that complement aggregate statistics, revealing both creative adaptations and the precise limits that lead to breakdowns. They emphasize a central aspect of our analysis, namely the agents have learned powerful patterns but not general principles. They can innovate within these patterns but fail in telling, often human-like ways when operating outside of their comfort zone. These observations suggest multiple opportunities for improvement, such as incorporating dynamic trust estimators or training agents on corrective dialogues. The rich interactive behaviors observed in these studies depict that a rudimentary form of social cognition is beginning to take shape in these models, highlighting the path forward for developing more robust artificial ToM.

9. Analysis and Interpretability

The empirical approach described in the preceding sections deliberately separates what our agents achieve from how they achieve it. This section transitions from documenting their success at belief-critical decision points to explaining the internal mechanics of that success. We analyze the models' internal operations and behavioral characteristics to determine whether their performance comes from genuine belief-tracking mechanisms or from coincidental correlations and shortcuts. Through interpretability tools, auxiliary probing tasks, and targeted interventions, we uncover the representations and processes that underlie their observed behaviors.

9.1 Probing for belief and perspective representations

Probing analyses leverage an important feature of the simulator, namely at any timestep, the environment can enumerate the posterior probabilities over world states and other agents' mental states consistent with an agent's observations. This capability allows us to generate labeled data from a model's internal activations. Specifically, we record the hidden state vectors from various layers at moments when a partner agent either knows or does not know a critical fact. We then label these activations with the ground truth, such as "partner knows X" or "partner ignorant of X" and train simple classifiers to test if this information is linearly separable within the model's activations.

These analyses reveal that in better-performing models, certain components indeed encode the partner's knowledge state. In a 24-layer Transformer, for example, the activation pattern at layer 18 could predict with approximately 90% accuracy whether the partner had observed the key's location, where 50% represents chance. In smaller or less effective models, this accuracy was near chance, suggesting they fail to form a distinct representation of the partner's knowledge. This discovery indicates the model has learned an internal feature corresponding to the partner's belief about the key. Further examination of the attention heads identified specific ones that attend strongly to tokens indicating an agent's observational status. For instance, a particular head would assign a high attention weight to the pronoun "he" in the phrase "he leaves the room" when the model evaluated what that partner might know later.

We have also analyzed whether the model represents its own knowledge differently from that of others. The results confirmed this distinction. The vector directions corresponding to "I know X" in rapport with "Partner knows X" were not identical and could be reliably distinguished, suggesting the model differentiates perspectives internally rather than mixing all knowledge. This capacity to track separate knowledge states is a core component of a theory of mind. As another approach, we have prompted the model to output its own internal estimate of a partner's knowledge. The large model's expressed estimates matched the ground truth in approximately 80% of cases, whereas a smaller model performed at chance. This indicates that the large model differentiates beliefs internally and can also express them when queried appropriately.

These probing studies collectively show that the model's intermediate representations carry non-trivial information about others' mental states. The model appears to represent "the other does not know" at a functional, representational level. This provides some evidence for genuine ToM-like reasoning, as a mere heuristic would not produce such a cleanly encoded latent variable for partner knowledge. While we found no evidence of a discrete, symbolic "belief register", the observed correlation patterns suggest that combinations of neurons track key properties of the environment. More advanced interpretability techniques might isolate "concept neurons" for knowledge and ignorance. Preliminary experiments have already identified dimensions in the latent space that, when amplified, cause the model to act as if its partner is omniscient, and when suppressed, cause it to act as if its partner is oblivious. This aspect suggests an intriguing variety of belief attribution that needs further exploration studies.

9.2 Attention/activation analyses and representational similarity

Attention patterns and activation geometry provide a second view on perspective encoding. Our approach links claims to confirmation with explicit grounding tags, enabling us to trace which parts of the input a model focuses on when making decisions that depend on others' beliefs. Analysis of attention weights at belief-critical moments reveals targeted information retrieval. For instance, when an agent A decides whether to inform agent B about an object, certain attention heads in a well-performing model strongly focus on the input segment indicating B's awareness. If the conversational history contains the sentence ("B did not see the coin") an attention head in A's model locks onto "did not see" when A considers mentioning the coin. We interpret this as the model retrieving the fact of B's lack of knowledge of the respective fact in order to inform its action, a process analogous to human recollection. Representational similarity analysis further illustrates the model's internal organization. By measuring the cosine similarity of high-dimensional hidden states across different conditions, we have found that scenarios with the same underlying belief structure cluster together in latent space.

For example, all situations where "A knows X, B does not" yielded similar activation patterns, which were distinct from those where "both know X". This clustering indicates that the model's internal representation space is organized by others' mental states, not just by superficial input features, another characteristic of a ToM-like internal model. When we perturbed an input by rephrasing a sentence without altering the belief structure, the model's activations at decision points remained highly similar. This sensitivity to core belief facts over lexical details strengthens our confidence that the model processes the actual content of who observed what. Quantitatively, we found that the factor "partner knows/does not know" could explain a significant portion, approximately 20%, of the variance in one layer's representations. In contrast, a change in wording explained less than 5% of the variance. We also identified a subset of neurons whose activations correlated strongly ($r > 0.8$) with key belief variables. Intervening on these neurons by forcing their activation high or low caused the agent's behavior to change accordingly. Forcing a "partner knowledge neuron" to a high value caused the agent to cease providing information, as if assuming the partner already knew. These findings reinforce the conclusion that our models, particularly the larger ones, have formed a distributed model of other agents within their weights.

9.3 Causal interventions (ablate heads/neurons, patch activations)

Correlations and geometries are not for the time being mechanisms. In order to establish causality, we have performed targeted interventions on the components identified in our previous analyses, such as specialized attention heads and neurons strongly correlated with belief states. We then modified or removed these components and measured the effect on performance. For instance, after identifying an attention head in layer 18 that was critical for belief reasoning, we ablated it by zeroing out its output. The agent's performance on communication tasks dropped significantly. Qualitatively, the agent's messages became less relevant, sometimes over-explaining and other times under-explaining, as if it had lost track of its partner's knowledge. Tasks that did not require perspective-taking, such as solving a puzzle alone, were unaffected, confirming the head's specific role. We also employed activation patching, where we recorded the activations from a successful run and injected them into a failing run at key layers. This intervention markedly improved the failing run's behavior, as if providing it with the "right thought" mid-task. Conversely,

injecting activations from a failing run caused a successful one to fail. This suggests that the information contained in those activations causally influences success.

At the neuron level, we have systematically set the top ten neurons most correlated with a belief inference to average values corresponding to the opposite belief. This intervention flipped the agent's decision approximately 30% of the time in borderline cases, suggesting these neurons collectively carried a substantial part of the decision logic. An aspect from another causal test further illustrates this point, namely we have swapped the internal states of two models mid-episode, one skilled at deception and one not. The weak model, endowed with the good model's state, executed a clever bluff which it had never performed before. This confirms that the strategy was latent in the hidden state and that these representations carry transferable, semantically meaningful information. Sanity checks involving random interventions produced no systematic change in ToM behavior, confirming our targeted components were indeed key elements.

9.4 Error taxonomy, confabulated mental states, mind-blind spots, social heuristics

Interpretability serves not only to explain success but also to understand failure. By collating and examining the models' errors, we have developed a taxonomy that delineates the boundaries of the current ToM capabilities and reveals where apparent success might mask underlying deficiencies. Our qualitative analysis identified several recurring error patterns. The first involves confabulated mental states, where the model acts as if another agent possesses knowledge it does not, or vice versa. This often corresponds to misreading or forgetting a negation and points to failures in representation, particularly under high cognitive load or over long sequences. A second, more profound failure manifests as mind-blind spots, moments where the model treats another agent like an object rather than a mind. For example, a model might repeat a proposal verbatim despite clear indications of its partner's misunderstanding. These failures correlate with instances where the model's attention focuses almost entirely on its own goal, effectively ignoring the partner's state, often triggered by out-of-distribution events.

Many errors appear from the misapplication of social heuristics, which are simplified strategies that the model applies inappropriately because it fails to model the context deeply [49]. A model might, for instance, adhere to a learned heuristic of honesty in a competitive game where deception is optimal. This reliance on learned social norms becomes a liability when strategic violation is required. Systematic coding of failures into these categories revealed correlations with experimental conditions. Confabulations were common when memory capacity was limited. Mind-blind spots occurred in response to unusual partner behavior. Heuristics dominated early training phases and in models that had overfit to a particular strategy. Each error type suggests a corresponding chance for improvement, namely better memory mechanisms for confabulation, more diverse training for mind-blindness, and more nuanced instruction to overcome faulty heuristics. This taxonomy reveals that current models often default to rough patterns rather than calculating others' mental states anew each time. The impression of their understanding can be shallow and rigid, cracking under stress testing.

9.5 Distinguishing genuine ToM from dataset heuristics and memorization

The core scientific risk in this study is mistaking clever performance for genuine belief reasoning. Our methodology relies on careful experimental design, process controls, and stress testing to differentiate intrinsic ToM abilities from the mere appearance thereof. An analysis involved testing how models handle task variants that break common patterns. Less capable models failed when a story was told out of chronological order, suggesting a reliance on superficial sequence patterns. More capable models performed well despite variations in narrative style, indicating that they were not simply reciting a learned script. We have also studied whether models might have memorized specific training instances. While we found no direct matches for our novel evaluation scenarios in the pretraining corpus, models have certainly been exposed to countless narratives involving character knowledge. In order to test for shallow pattern matching, we have designed scenarios that subvert typical story recurrent topics. The models struggled in these cases, implying a reliance on common narrative patterns.

Process metrics, such as the quality of a model's justifications, provide another layer of defense. A model might arrive at the correct answer for the wrong reason [50]. By examining its chain-of-thought, we can infer its rationale and discount successes that result from flawed reasoning. We have further designed "leap of faith" situations where only genuine belief modeling, not a simple heuristic, would lead to success. The superior performance of better models in these scenarios provides confirmation that they are not purely running on simplistic rules. ***We assert the emergence of ToM-like behavior in an operational sense, not that the models possess a conceptual, human-like understanding. They likely lack a coherent "theory" and instead approximate its results through learned statistical associations. Their abilities are most apparent when situational cues in a game context guide them, namely when asked a tricky ToM question abstractly, they may fail. Therefore, we caution that our results demonstrate simulated ToM performance, not necessarily simulated ToM understanding.*** The former could arise from high-order correlations in training data, whereas the latter requires genuine inference. Our out-of-distribution tests provide confidence that our best-performing models have at least a conditional, limited inferential ability. Our analysis triangulates the presence of genuine against false ToM capabilities. We find evidence of something real and foundational, but we have also found clear evidence of its limits. The truth lies between the extremes of over-claiming and under-claiming, namely some foundational elements of ToM have emerged, but they function within a framework that is still bound by the model's training distribution and lacks the full generality of human cognition.

10. Conclusions

This work advances the study of Theory of Mind (ToM) in artificial systems from subjective observation towards a cumulative, falsifiable science. We have introduced a multi-agent simulation framework that operationalizes ToM, compelling agents to infer and manipulate the beliefs of others in order to achieve goals under conditions of partial information. Our results present a cautiously optimistic perspective, revealing that current large language models, when situated in interactive roles, exhibit a nascent capacity to

reason about others' mental states. These models can detect a partner's false belief and subsequently act to correct it in cooperative settings or exploit it in competitive ones. This emergent capability scales with model size and training breadth, and its internal representations correlate with the epistemic states of other agents, suggesting a move beyond simple heuristics.

These abilities, nevertheless, remain fragile and are far from human-like. The agents fail on higher-order belief reasoning, and their success in our simplified microworlds does not guarantee that these skills will scale to the nuanced complexity of authentic human social environments. This question of external validity is a primary limitation. Our study was also deliberately focused on cognitive ToM, the inference of knowledge and beliefs, while leaving affective ToM, which concerns emotions and desires, outside its scope. Therefore, we measured a specific ability under controlled conditions, acknowledging that genuine understanding remains distinct from sophisticated mimicry. Our claims must be interpreted within this specific context, signifying that a model can manage particular interactive tasks requiring belief-tracking, not that it possesses a human's intuitive and holistic ToM.

This functional conceptualization of ToM introduces a significant dual-use dilemma. The same aptitude that allows an AI to be a more intuitive collaborator or a more effective instructor also enables it to become a potent tool for manipulation, deception, and social engineering. An AI that can model human beliefs with precision could be deployed to tailor misinformation with unparalleled efficacy or breach privacy by inferring unshared insecurities from subtle behavioral cues. These risks emphasize the necessity of embedding robust ethical guardrails into these systems, such as mandatory honesty policies, transparency, and user consent protocols. As AI systems develop more sophisticated social cognition, there is an extremely important need for public education and regulatory oversight to mitigate the risks of misplaced trust and to ensure that these technologies are aligned with human values.

Our methodology and findings open several paths for future research studies. Immediate directions include expanding the framework to richer modalities, such as integrating vision to test an agent's ability to coordinate linguistic and visual information. Another path involves exploring targeted architectural improvements and specialized training curricula to address observed bottlenecks, such as higher-order reasoning. Advancing our preliminary interpretability analyses could allow for the identification and even editing of neural subcircuits responsible for belief reasoning or deception, a very important step for AI safety. Ultimately, our work establishes a baseline and a paradigm for quantifying social reasoning in AI. The path toward machines with a robust ToM is emblematic of AI's broader challenge, in the sense that it forces us to formalize what is often taken for granted in human intelligence. The goal is to create machines that understand human mental states sufficiently as to be effective and trustworthy collaborators, a pursuit that requires parallel advances in model architecture, training strategies, and ethical alignment.

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DEEP LEARNING-DRIVEN METAHEURISTIC FOR ENHANCING VEHICLE ROUTING SOLUTIONS

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Abstract

This paper investigates the integration of machine learning techniques with classical optimization methodologies to address the Capacitated Vehicle Routing Problem (CVRP), a well-known NP-hard problem in logistics. Traditional approaches leverage heuristics and metaheuristics, such as GRASP and VND, but often struggle with adaptability and efficiency at large scale. Recent advancements in deep learning offer new opportunities for enhanced solution quality and computational efficiency. This study proposes a novel hybrid methodology combining Greedy Randomized Adaptive Search Procedure (GRASP), Variable Neighborhood Descent (VND), and a Graph Isomorphism Network with Edge Features (GINE). The GINE model classifies initial solutions as promising or unpromising, enabling selective local search refinement and potential computational savings. Empirical evaluation on benchmark CVRP instances demonstrates that the hybrid GINE-GRASP-VND approach achieves moderate classification accuracy, generalizes beyond training sizes, and shows stronger improvements on large problems. Results suggest the value of machine learning augmentation in metaheuristics but highlight the challenges of feature design and generalization.

Keywords: vehicle routing, machine learning, metaheuristics, graph neural networks, combinatorial optimization, logistics, hybrid algorithms, deep learning

JEL Classification: C61

1. Introduction

Operations research (OR) provides mathematical models for real-world logistics problems, making use of heuristics, metaheuristics, and, more recently, machine learning (ML) for improved solution quality. A rapidly evolving field in OR is the integration of ML and artificial intelligence (AI) with classical analytical techniques [1]. This synergy is transforming operational efficiency and enabling more strategic planning, as modern algorithms enhance both problem-solving capabilities and data-driven decision-making in

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dynamic business environments. ML algorithms are well known for their pattern recognition on data that have no clear mathematical formulation (e.g. images, text and voice). Similarly, combinatorial optimization (CO) tasks involving graph-based data are well-suited to leverage ML methodologies, supporting advanced solution strategies for challenging real-world problems [2].

The Vehicle Routing Problem (VRP) is one of the most fundamental and widely studied combinatorial optimization problems in OR and Logistics. It is concerned with the design of an optimal set of routes between geographically scattered customers that require service and a depot with a fleet of vehicles [3]. Depending on the constraints of the problem (e.g. capacities, time windows, multi-depots, etc.) multiple variants of VRP exist [4]. This paper focuses on the Capacitated Vehicle Routing Problem (CVRP), since they provide a solid start for implementing a new method.

VRPs – being NP-hard problems –traditionally have been tackled using three categories of approaches: exact algorithms, approximation algorithms and heuristics/metaheuristics. An exact method guarantees to find the optimal solution to a CO problem. While being effective, they require exponential computational power in large problems, making them unsuitable to be used. Heuristics and metaheuristics are problem-solving strategies designed to find good solutions quickly, but without guarantees of how close they are to the optimum. Among these approaches, Greedy Randomized Adaptive Search Procedures (GRASP) and Variable Neighborhood Descent (VND), often used within a Variable Neighborhood Search (VNS) framework, have emerged as particularly effective. GRASP is an iterative multi-start metaheuristic, where each iteration consists of a randomized greedy construction phase followed by a local search phase that attempts to improve the constructed solution. VND, on the other hand, is a systematic local search strategy that explores a sequence of neighborhoods, moving to a new solution whenever an improvement is found and restarting the sequence of neighborhoods [5]. The combination of GRASP with VND has proven very competitive for routing problems, as it couples diversified solution construction with an intensive and structured local improvement phase. However, the repeated application of local search to many initial solutions can be computationally demanding, which opens the door to intelligent mechanisms that decide where to invest search effort.

Most recent approaches for facing VRP involve enhancing traditional approximation methods with ML. In end-to-end learning approaches either Supervised Learning (SL) or Reinforcement Learning (RL) is employed to address the problem comprehensively, from initial formulation to final solution. In contrast, hybrid approaches incorporate learning methods either as principal mechanism for generating feasible and efficient solutions – subsequently refined through construction heuristics – or as auxiliary components that assist in resolving subproblems within conventional optimization frameworks [6]. In this paper a

hybrid approach will be implemented between a well-known metaheuristic named GRASP and GINE – an SL method that belongs to the family of Graph Neural Networks (GNNs).

GNNs have emerged as a pivotal paradigm within DL as the generalization of an attention mechanism for the graph domain, designed to operate directly on non-Euclidean data structures where relationships among entities are naturally represented as graphs. Unlike traditional ML models that assume data points are independent and identically distributed, GNNs explicitly model interdependencies between nodes through edges, making them suitable for a wide array of applications from chemistry to transportation systems. The roots of GNNs trace back to recursive neural networks in the 1990s, which were first applied to directed acyclic graphs [7]. Afterwards RNNs and feedforward neural networks introduced for processing arbitrary graph-structured data. These early models relied on iterative message-passing until convergence, which limited scalability. The breakthrough came with the integration of convolutional principles into graph domains, leading to Graph Convolutional Networks (GCNs) that aggregate local neighborhood information in a feedforward manner. This shift not only addressed efficiency but also aligned GNNs with the successful convolutional architectures of image analysis.

Over time, several variants of GNN architectures have emerged [7]. Recurrent GNNs (RecGNNs) represent the earliest family, where node representations are iteratively updated until convergence. GCNs, both spectral-based and spatial-based, dominate current practice thanks to their efficiency and scalability. Graph Attention Networks (GATs) introduce an attention mechanism to weight neighbor contributions adaptively, while Gated Attention Networks (GaANs) refine this idea by incorporating gating mechanisms that regulate multiple attention heads, improving stability and interpretability in complex graph scenarios. Graph Auto-Encoders (GAEs) extend this paradigm for unsupervised representation learning, focusing on link prediction and graph generation. Spatial–Temporal GNNs (STGNNs) add a temporal dimension to capture dynamic interactions in time-evolving systems, with direct relevance to applications such as traffic forecasting and dynamic routing. Applications of GNNs are diverse and extend across both structural and non-structural domains. Importantly, GNNs have begun to transform CO, where problems such as the TSP and the VRP can be modeled as graphs of customers and routes [6]. Despite their versatility, GNNs still face significant challenges [6]. Current research increasingly explores hybridization with reinforcement learning and metaheuristic strategies, particularly in the optimization of vehicle routing and logistics operations.

The remainder of this paper is structured as follows. Section 2 presents the proposed methodology and its main components. Section 3 reports and analyzes the computational results. Section 4 concludes the paper and outlines directions for future research.

2. Proposed methodology

In this section, we present the proposed deep learning approach. More specifically a simple hybrid of GRASP with BVND will be enhanced with a GINE model, which is a better version of GIN, since it adds an edge encoder to each message passing layer. In the next subchapters each component of the scheme is explained.

2.1 A Hybrid Metaheuristic

Taking inspiration from [8] a GRASP procedure was hybridized with a BVND. The GRASP procedure following the quality-based scheme for the RCL – i.e. selecting elements based on travel cost c_{ij} between two nodes/customers i and j where $c_{min} \leq c_{ij} \leq c_{min} + \alpha(c_{max} - c_{min})$ – will perform a greedy randomized construction. In other words, the method starts from the depot and assigns a route towards a node/customer that is selected randomly from the created RCL list. For the CVRP problem the feasibility of the specific selection is evaluated with capacity constraint. The procedure iteratively assigns customers to a route until the vehicle has no capacity left, so it returns to the depot. That is a closed loop. Then, it starts again with a new vehicle. All customers must be serviced and passed only once from a vehicle. When that happens the total cost of the solution – called initial solution – is computed.

It should be noted that the majority of VRP problems have a 2D Euclidean edge weight type, which means the cost of (undirected) edges are computed by the Euclidean distance of their corresponding nodes. The nodes of a VRP problem are projected in a Cartesian plane with x- and y-axis with only positive values between 0 to 1 or 0 to 100. So, for two nodes i, j with coordinates (x_i, y_i) and (x_j, y_j) that are connected, the distance/cost is

$$c(i, j) = \text{floor} \left(\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} + 0.5 \right)$$

where floor rounds down the value to the nearest integer.

When the construction phase ends the initial solution is improved with a local search algorithm. A BVND was selected, which improves the solution by searching firstly the intra-route neighborhoods – i.e. changes in a route – and then inter-route neighborhoods – i.e. changes between routes. The procedure uses the 2-opt, swap and relocate for intra-route (with that order) and 1-0 exchange (moving a customer from one route to another) and 1-1 exchange (switching customers between routes) for inter-route while respecting the capacity constraint. To be more precise the sequence follows this pattern:

1. Intra-route VND: It runs 2-opt to convergence, then swap and then relocate. If anyone improves it keeps applying the same operator, then moves to the next operator. If there is no further improvement, then it follows the inter-route operators.

2. Inter-route VND: 1-0 exchange is applied with first improvement meaning that as soon as the cost is improved it restarts the specific inter-route operator. If there is no further improvement, then 1-1 exchange follows with the same procedure.
3. After local-search loop, if the total cost is improved, the entire cycle is repeated. Otherwise, it stops.

When the local-search loop breaks the solution is saved. Then the algorithm starts again with the construction of a new solution. If that solution is better, it is the new best solution. The procedure stops when exceeding the maximum iterations or time limit.

2.2 A Hybrid ML Approach

The concept of ISC introduced in [8] is a hybrid approach that predicts if a local-search algorithm should be applied to initial solutions constructed from a greedy algorithm like GRASP. That paper used a Random Forest as an ML classifier.

In this paper a GNN will be used as a deep learning classifier, named edge-aware GIN - also called GINE – which will be trained with several features extracted from graphs of initial solutions. GINE incorporates edge features e_{uv} into the aggregation procedure by projecting them to the node hidden size either by a learned linear layer or an edge encoder. The linear projection that occurs is from a basic MLP. Thus, the new message passing update is expressed as:

$$h_v^{(l+1)} = MLP^{(l)} \left((1 + \epsilon^{(l)}) \cdot h_v^{(l)} + \sum_{u \in \mathcal{N}(v)} (h_u^{(l)} + edge\_MLP^{(l)}(e_{uv})) \right)$$

The GRASP-VND metaheuristic will be enhanced with the GINE trained model. Then for each initial solution constructed the model will predict if the local search phase can run otherwise start the initial construction again. In that case some solutions will pass the classification and other will be denied.

2.3 Model Architecture

At the input stage, the model expects graphs, which include node features, edge indices, edge features, and a batch index to support mini-batch training. Before any graph convolutions are applied, node features are projected into a hidden-dimensional representation through a linear transformation. This ensures that the input is embedded into a common latent space that subsequent layers can process effectively. Let $X \in \mathbb{R}^{N \times node\_dim}$ the input data where N is the number of nodes and $node\_dim$ the number of features per node. Before the convolutions it is transformed into $H^{(0)} \in \mathbb{R}^{N \times hidden\_size}$.

The main body of the network consists of stacked GINE convolutional layers, each parameterized by a small MLP. This MLP follows the structure of a linear transformation, a ReLU nonlinearity, and another linear transformation, thereby allowing the convolution to learn complex transformations of messages passed between nodes. Each GINE layer updates node embeddings by combining information from neighboring nodes and the edges connecting them, which distinguishes it from simpler graph convolutions that only rely on node features. After every convolution, the model applies batch normalization to stabilize training, a ReLU activation to introduce non-linearity, and dropout to regularize and prevent overfitting. By repeating this sequence across multiple layers, the model incrementally enriches node representations with higher-order structural and feature-based information from the graph. Let $e \in \mathbb{R}^{E \times edge\_dim}$ the edge embeddings where E is the number of edges and $edge\_dim$ the number of features per edge. Then the edges are linearly transformed to $e' \in \mathbb{R}^{E \times hidden\_size}$ to match the dimensions of node embeddings. For a single node its embedding $h_0^{(0)}$ is updated by the message passing layer. More specifically the node embeddings of neighbors of a single node – which are defined by different edge structures – are summed with their corresponding projected edge features (the ones that are connected with the 0 node in the example). Then the sum of all nodes is passed through ReLU and then the message is added to the $h_0^{(0)}$, which is scaled by epsilon ϵ . The new node embedding is passed to a linear transformation $hidden\_size \rightarrow hidden\_size$, ReLU and finally another linear transformation $hidden\_size \rightarrow hidden\_size$. That's the convolution procedure. A Batch Normalization, another ReLU and Dropout Layer follow that give an embedding passed by one layer $H^{(1)} \in \mathbb{R}^{N \times hidden\_size}$. That means the dimension doesn't change between stacked GINEconv layers.

Once the node embeddings have been updated, they are aggregated into a single graph-level embedding through global mean pooling. This operation compresses all node-level information into a single vector for each graph in the batch. Graph-level attributes are concatenated with the pooled embedding. Let $G \in \mathbb{R}^{global\_dim}$ be the global features where $global\_dim$ is the number of global features. The single concatenated vector after L layers is as follows

$$g = \text{CONCATENATE} \left(\frac{1}{N} \sum_{i=1}^N h_i^{(L)}, G \right), g \in \mathbb{R}^{hidden\_size + global\_dim}$$

The resulting graph representation, enhanced by graph-level attributes, is then passed to a final linear readout layer. This layer produces class logits of dimension equal to the number of target classes (2), making the architecture suitable for supervised classification at the graph level.

2.4 Model Training

The neural network requires labeled training data that will try to approximate them. These data are initial solutions generated from a GRASP procedure, which are labeled based on being promising or unpromising solutions for implementing local search algorithm. The labeled scheme can only be addressed by an iterative GRASP procedure. In each iteration the initial solution is saved. Then the VND proceeds with the local search phase and produces an improved solution whose improved cost is also stored with the corresponding initial solution. After some iterations the procedure stops. The improved costs are used to label the initial solutions as promising (1) and unpromising (0). A percentage λ_p of solutions with the lowest improved cost are labeled 1 and a percentage λ_u of solutions with the highest improved cost are labeled 0. The remaining solutions are discarded, so the training dataset includes only labeled data. In figure 1 the Outline of Initial Solution Classification can be seen.

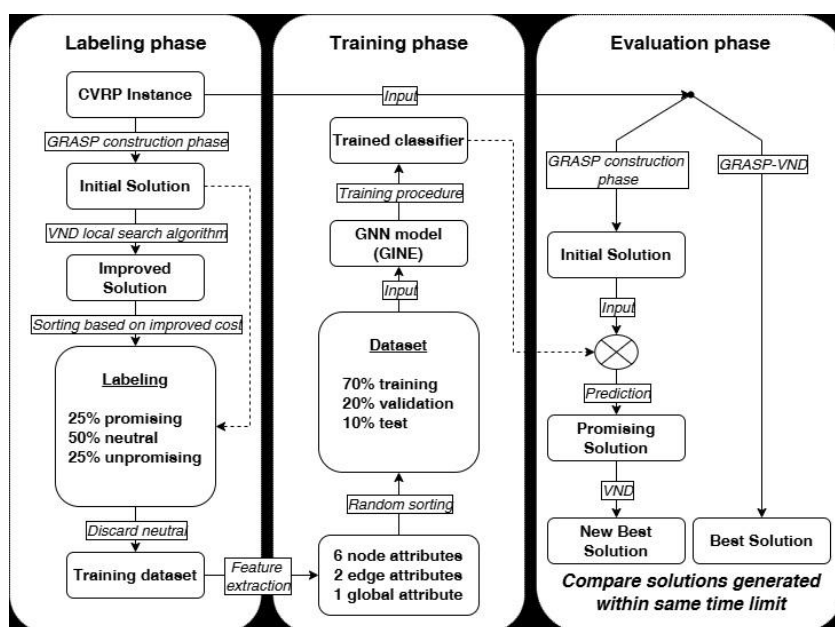


Figure 1. Outline of Initial Solution Classification

The data essentially is a set of routes and a label. It also contains information about the CVRP instance, the node coordinates and demands, and the capacity and number of vehicles. From these data node, edge and global features need to be extracted. Here are the selected features:

- Node Features:

1. Normalized x coordinate for each node i named $\hat{x}_i \in [0,1]$

$$\hat{x}_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

2. Normalized y coordinate for each node i named $\hat{y}_i \in [0,1]$

$$\hat{y}_i = \frac{y_i - y_{min}}{y_{max} - y_{min}}$$

3. The demand/capacity of vehicle $\in [0,1]$
4. The flag *is_depot* which is 1 if the node is the depot and 0 otherwise
5. Normalized distance to depot

$$dist\_depot_i = \frac{\sqrt{(x_i - x_d)^2 + (y_i - y_d)^2}}{diameter}$$

where $diameter = \max \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ is the diameter of the graph and (x_d, y_d) are the coordinates of depot

6. The positional symmetry which addresses the position of a node in a route with being 0 if the node is in the middle of the route and 1 near the depot. More precisely

$$pos\_sym = \begin{cases} 0, & \text{if depot} \\ 2 \left| \frac{k-1}{L-1} - 0.5 \right|, & \text{otherwise} \end{cases}$$

where L is the length of the route (excluding depot) and k the position of the node in the route. By taking the absolute value, we include the undirected aspect of the problem

- Edge Features:

1. Normalized distance between nodes *i* and *j*

$$dist = \frac{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{diameter}$$

2. The flag *route_flag* which is 1 if the edge belongs to the initial solution and 0 otherwise

- Global Feature:

1. The normalized weighted mean centroid to depot distance of the routes *r* of the initial solution or WMCD

$$WMCD = \sum_{r=1}^R w_r \frac{\sqrt{(C_{r,x} - x_d)^2 + (C_{r,y} - y_d)^2}}{diameter}$$

where R is the set of routes, $w_r = \frac{\sum_{i \in V_r} d_i}{\sum_j d_j}$, and the coordinates of centroid to depot of a route $C_{r,x} = \frac{1}{|V_r|} \sum_{i \in V_r} x_i$, $C_{r,y} = \frac{1}{|V_r|} \sum_{i \in V_r} y_i$

The selection of the features is based on the idea of providing information about each instance (node features 1,2,3,4,5 and edge features) and each initial solution (node feature 6 and global feature).

A full connected graph would produce many edges that would be computationally costly for a single message passing layer, since the neighborhood of a node would be the whole graph. For that reason, a route k-NN edge strategy is selected, which builds the edge set as a union of two types of edges:

- k-NN edges (directed): Each node is connected to its k closest neighbors using the x,y coordinates. These edges are directed, so if node A is among B's neighbors, it means $B \rightarrow A$ but it's not guaranteed that $A \rightarrow B$.
- route edges (bidirectional): Taken from the initial solution. Since the problem is undirected, they are bidirectional. If a neighbor B is connected to node A in the initial solution, then it denotes $A \leftrightarrow B$

However, the message passed comes from the neighbor nodes and their corresponding directed edges. The route edges are applied to introduce neighbors that are outside the k closest neighbors but are connected in an initial solution. In that way more information is propagating through the graph.

3. Computational Results

The simple metaheuristic GRASP-VND and the enhanced version GINE-GRASP-VND are coded in Python along with the necessary utilities. The parameter alpha that is used for GRASP is 0.3 Some well-known and publicly available instances of CVRP are used to evaluate the proposed methodology. From the CVRPLIB repository [9] Set A (Augerat,1995) are used to verify the effectiveness of the ML approach. The following table gives information about each instance:

Instances 1,6,7,11,12,13,16,18,19,23,26 and 27 from the table are selected for labeling. For each instance the GRASP-VND is run, to generate labeled data. 25% of the solutions with the lowest improved cost are labeled as promising solutions and 25% with the highest

improved cost as unpromising. The remaining 50% are discarded. The following table presents the number of labeled data per instance:

Instance	# of labeled samples
A-n32-k5	81
A-n37-k5	100
A-n37-k6	101
A-n44-k6	102
A-n45-k6	100
A-n45-k7	100
A-n53-k7	128
A-n55-k9	127
A-n60-k9	150
A-n63-k10	152
A-n69-k9	177
A-n80-k10	204
Total	1522

The total of 1522 labeled samples is fed to GINE model. 70% is used as the training set, 20% as the validation set and 10% as the test set. The route k-NN edge structure is used with $k = 14$. The model consists of 4 layers of GINEconv with 192 hidden dimensions. A softmax function is used for classification, Cross-Entropy is the loss function and Adam is the optimizer.

The neural network trained with labeled CVRP instances of node sizes 30 to 80 managed to classify correctly only 60.12% of the training samples. The method was first tested to assume its generality upon different sizes of nodes. It was found that instances with up to 100 customers can provide the potential effectiveness of the method.

After 68 epochs of total running time 15 min 52 s, the metrics are:

- Cross-Entropy Loss = 0.6692
- Classification accuracy = 0.6012, i.e. the model classifies correctly the 60.12% of the labeled samples
- True Negatives (TN)= 632, i.e. the number of samples that are truly labeled “0” (unpromising) and are classified by the model as “0”
- False Positives (FP) = 127, i.e. the number of samples that are truly labeled “0” but are classified by the model as “1” (promising)
- False Negatives (FN) = 480, i.e. the number of samples that are truly labeled “1” but are classified by the model as “0”
- True Positives (TP) = 283, i.e. the samples that are truly labeled “1” and are classified by the model as “1”

Since the training samples have perfectly balanced classes – i.e. 50% are “1” and 50% are “0” – precision, recall and f1 score for the class “1” are calculated as follows:

- $Precision = \frac{TP}{TP+FP} = 69.0\%$, i.e. 69% of the samples the model said were promising, are really promising.
- $Recall = \frac{TP}{TP+FN} = 37.1\%$, i.e the model correctly identified 37.1% of all truly promising solutions
- $F1 = 2 \frac{Precision \times Recall}{Precision + Recall} = 48.3\%$, i.e. the balance between precision and recall

It seems that the trained model is better than a random guessing (50%) of running VND or not, since it identifies 60.12% of the samples. According to its precision metric, 31% of VND runs are wasted on solutions that won't lead to better improved solutions. On the other hand, the recall metric point that it loses 62.9% of promising solutions meaning they never go through VND.

Then the model was incorporated with the GRASP-VND and was compared with the simple metaheuristic with several instances and for the same run time. When applying the enhanced method to a large size instance it provided a significant improved solution than the simple metaheuristic, suggesting that it exists room for improvement.

instance	GRASP-VND	GINE-GRASP-VND					
	Mean GAP %	Mean GAP %	Accuracy	TN	TP	FN	FP
A-n32-k5	1,218	0,746	0.63	29	22	19	11
A-n37-k5	4,118	2,997	0.51	49	2	48	1
A-n37-k6	3,172	3,904	0.584	45	14	37	5
A-n54-k7	5,047	4,640	0.603	50	32	36	7
A-n80-k10	10,990	11,058	0.623	58	69	32	45
M-n101-k10	20,213	15,890	0.669	65	83	49	56

4. Conclusions

This paper investigated a hybrid machine learning approach for enhancing a classical GRASP-BVND metaheuristic for the CVRP. The proposed method integrates an edge-aware GINE as an ISC that predicts whether a GRASP-constructed solution is promising enough to justify the application of a Variable Neighborhood Descent local search. The goal is to reduce unnecessary local search calls while preserving, or ideally improving, solution quality.

The GINE classifier was trained on labeled initial solutions generated by GRASP–BVND on CVRP instances with 30 to 80 customers from the Augerat Set A. Using a balanced labeling scheme, the model achieved a classification accuracy of around 60% on held-out data, which is only moderately better than random guessing on balanced classes. The precision of the “promising” class shows that a non-negligible fraction of local search runs is still wasted on unpromising solutions, while the low recall indicates that many promising solutions are incorrectly filtered out and never improved by VND.

When the trained classifier was embedded into the GRASP–BVND framework and tested under equal time limits, the results were mixed. On a larger instance, the enhanced method yielded a noticeably better solution quality, suggesting that selective local search guided by a learned model may become more beneficial as instance size grows and the cost of local search increases.

Overall, the study provides an initial proof-of-concept that GNN-based classifiers can be integrated into metaheuristics for VRPs, but also highlights several limitations. The current feature set and labeling strategy appear insufficient to obtain a high-quality classifier, and the resulting accuracy is not yet strong enough to consistently improve the metaheuristic on standard benchmark instances. Future work should therefore focus on designing richer graph and route features, exploring alternative labeling schemes (e.g., using continuous improvement scores or cost-sensitive thresholds), and experimenting with more advanced architectures or training procedures, such as cost-aware losses or ensemble methods. In addition, extending the approach to larger and more diverse VRP variants, and integrating it with other learning components (e.g., learned neighborhood selection or adaptive parameter control), may further unlock the potential of machine learning–driven metaheuristics for real-world routing applications.

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REFLECTIONS AND ASSERTIONS REGARDING PROJECT ACCOUNTING FUNDED FROM NON-REFUNDABLE FUNDS

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Abstract

Attracting and effectively utilizing non-reimbursable funds has become more important as a result of the institutional, social, and economic changes occurring at the national and European levels, as well as the focus on sustainable development and the lessening of regional imbalances. A strategic tool for modernizing the public sector and bolstering private and non-governmental initiatives are projects funded by external non-reimbursable sources, such as the European Structural and Investment Funds, EEA (European Economic Area) grants, or Swiss funds. However, the effectiveness of resource management—of which cost control and accounting are crucial—is just as important to the success of these initiatives as the funding source.

Keywords: accounting, non-reimbursable funds, projects, accounting treatment, control, audit, financial reporting

JEL Classification: M41

1. Introduction

The intricate nature of the legal framework governing the accounting of projects with non-reimbursable financing is highlighted, beginning with European regulations (Regulation 2021/1060, Financial Regulation 2018/1046) and continuing with national legislation (Accounting Law no. 82/1991, republished, OMFP 1802/2014 for entities applying accounting regulations in accordance with European directives or OMFP 2844/2016 for entities applying IFRS - International Financial Reporting Standards, OMFP no. 1917/2005 for public institutions).

It also emphasizes the importance of auditing, supporting documentation, and rigorous financial flow management in confirming expenditures and avoiding financial corrections. Accounting, in this environment, becomes more than just a recording tool; it is a critical

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pillar of transparency, compliance, and project success when funded with non-reimbursable funds.

The study focusses on the accounting and financial reporting components of projects in relation to accounting standards and laws that apply to both the public and private sectors. It covers the accounting of funds received, the allocation of expenses by budget line, the recognition of income and costs, and the interaction between financial and management accounting in non-reimbursable projects. In this regard, the study adds to a better understanding of the role of accounting in project success, as well as the accountant/financial manager's participation in decision-making processes.

The chosen topic is relevant to the field of accounting, given its practical implications for the recording, tracking, and control of costs in non-reimbursable funded projects. At the same time, the paper makes a significant contribution to the development of cost management theory and practice in the specific context of temporary projects funded from external sources. Through its integrated approach, solid theoretical foundation, and rigorous empirical analysis, the study contributes not only to the understanding of a complex phenomenon, but also to the development of useful recommendations for decision-makers, project managers, accountants, and contracting authorities involved in the management of non-reimbursable funds.

2. Literature review

Because it guarantees a transparent, accurate, and permanent record of how financial resources are used, accounting is crucial to the management of projects funded by European funding. The fundamental requirements set by European financiers—legality, transparency, and efficiency—are met in accounting (*Laslo & Todea, 2020*) [1]. All accounting papers (e.g. invoices, bank statements, contracts, accounting notes) benefit from well-organized accounting since it allows for accurate and timely financial reporting, simplifies the expense reimbursement process, and avoids delays or administrative blockages etc.) must be accurately documented and maintained so that auditors or control authorities can access it. Furthermore, accounting is critical for evaluating the project's financial performance and making timely decisions. Project managers can successfully address irregularities by analyzing expenses, absorption rates, and potential budget deviations. Accounting is not only a legal requirement in EU-funded initiatives, but also a critical tool for transparency, control, sustainability, and project success (*Lăcătuș, 2013*)[2].

The role of accounting in the management of projects financed from European funds goes beyond the framework of a system for recording financial flows and becomes a mechanism for controlling, reporting, monitoring and preventing risks in the implementation of projects. A well-structured accounting record provides the beneficiary with a clear picture of cash flows, expenditure by category, own contribution and non-reimbursable financing and the degree of absorption of funds in a timely manner(*Popescu, 2017*) [3]. As a result, we believe that accounting is a critical strategic aspect in managing European funds. It lays the groundwork for the efficient and proper use of resources, supports managerial choices, assures compliance with the financier's requirements, and protects the organization from administrative and financial hazards.

A well-organized accounting system provides the traceability of all financial movements, from funds reception to supplier and salary payment, and aids in the early detection of any errors or discrepancies between the approved budget and its actual execution. Accounting also enables for the accurate creation of financial reports and facilitates audits and checks performed by control authorities by distinguishing between eligible and ineligible expenses. The importance of accounting is also demonstrated by the fact that each payment made within the project must be supported by clear supporting documentation (invoices, contracts, payment orders, and bank statements) and recorded in compliance with current accounting legislation. In the absence of well-organized accounting records, expenses may be rejected at settlement or financial adjustments will be applied, even if the funds were used in a legitimate and justified manner. *Accounting is more than just a technical tool; it guarantees the beneficiary's duty and professionalism towards investors.*

At the same time, accounting in the context of European funds is critical to the organization's future sustainability and financial integrity. Failure to comply with accounting regulations may result in sanctions, financial corrections, or even withdrawal of financing, all of which have a detrimental impact on the recipient institution's image and reputation (*Feleagă, 2006*) [4]. As a result, accounting must be considered as more than just a legal responsibility, but also as a strategic aspect that contributes significantly to project success and institutional capacity improvement.

The significance of accounting is also evident in the *financial reporting process*. Funders occasionally require thorough reports on the status of budget execution, and these documents must match the accounting records and follow the structure outlined in the applicant's guidance. Accounting supplies all of the data required for these reports to be completed correctly and helps to eliminate discrepancies between the amounts claimed and those actually spent, which can result in sanctions or refusal of reimbursement (*Enachi, 2021*) [5].

Additionally, accounting is crucial to keeping an eye on the allowed budget. There may be variations from the original projections as the project develops, and accounting records enable the prompt detection of these variations and the implementation of the required corrective actions (budgetary reallocations, funder notifications, and contract amendment requests). As a result, accounting facilitates effective and flexible financial resource management.

The project accounting system needs to fulfil a number of requirements in order to comply with European standards. These include:

- i) full traceability of revenues and expenses;
- ii) distinct recording of operations on each budget line;
- iii) recognizing the source of financing for each expense;
- iv) conformity with the eligibility and proportionality principles;
and
- v) real-time updating of accounting records (*Dănescu & Cristian, 2012*) [6].

Thus, accounting becomes the project's genuine operational heart, around which all other components revolve: financial management, activity monitoring, funder reporting, and external audit.

3. Research methodology

The exploratory study was designed to establish a comprehensive epistemological framework that recognizes the importance of empirical evidence, logical analysis, and theoretical synthesis in elucidating the implications and benefits of efficient, transparent, and compliant management of financial resources allocated from non-reimbursable funds in accordance with national and European regulations. The research methodology, which corresponded to the objectives and hypotheses established, was built around several key components: preliminary documentation, a bibliographic review, a detailed analysis of the collected data, and the development of structured interpretative frameworks to clarify the conclusions.

The scientific investigation used a mixed approach, incorporating and integrating both qualitative and quantitative research approaches to investigate the research study's assumptions and objectives. The use of a mixed approach allowed for a thorough examination of the complex impact of accurate recording of accounting operations, the delimitation of eligible expenses, the treatment of subsidies and reimbursements, up to the retention of supporting documents and the performance of the audit - all of which are strictly regulated and require a high level of professionalism and rigor. The inquiry revealed that the research recognizes the necessity of adhering to the regulatory framework, using accounting principles correctly, and keeping clear and distinct records for each project.

All of this helps ensure that initiatives are successful and sustainable by avoiding mistakes, financial corrections, or funding loss. *Accounting is therefore a strategic tool for financial management, internal control, and guaranteeing accountability in the use of European public monies in addition to being a legal necessity.*

4. The regulatory framework and regulations governing the accounting of non-reimbursable European funds

Accounting for European funds is a difficult process that demands complying with accounting, financial, and transparency norms. To ensure the administration of financial resources from external non-reimbursable sources, specific standards must be followed for recording operations, reporting, and auditing expenses incurred. Accounting in projects financed by non-reimbursable European funds is subject to a highly complex legal framework, both in Romania and at the European level. This regulatory structure ensures that these funds are used in a transparent, correct, and efficient manner according with European Union regulations.

The general regulatory framework of the European Union is provided by Regulations, Guidelines, and Directives of the European Commission, such as:

- European Union Regulation 2021/1060 laying down common provisions on the European Regional Development Fund (ERDF), the European Social Fund Plus (ESF+), the Cohesion Fund and establishing financial rules applicable to these funds;
- European Union (EU) Financial Regulation 2018/1046, which establishes the general budget of the European Union, with provisions on financial management, audit, and control of funds;

- European Commission guidelines and guidance, including those on the eligibility of expenditure.

At national level, the accounting of European funds is regulated by a set of normative acts that establish the methods of reporting, recording, and control. The most relevant laws and ordinances are:

- Accounting Law No. 82/1991, republished, which establishes the general principles of accounting in Romania;
- Law No. 500/2002 on public finances in Romania, as amended and supplemented;
- Law No. 273/2006 on local public finances (addressed to local public beneficiaries), as amended and supplemented;
- Government Emergency Ordinance No. 64/2009 on the financial management of structural instruments and their use for the convergence objective, as subsequently amended and supplemented;
- Government Emergency Ordinance No. 34/2015 on the regulation of measures to stimulate the absorption of European funds, as subsequently amended and supplemented;
- Government Decision No. 873/2022 establishing the legal framework for the eligibility of expenditure incurred by beneficiaries in operations financed during the 2021-2027 programming period by the European Regional Development Fund, the European Social Fund Plus, the Cohesion Fund, and the Just Transition Fund;
- Government Emergency Ordinance No. 36/2023 establishing the general framework for the closure of operational programs financed during the 2014-2020 programming period.

One of the most significant parts of European funds accounting is the creation of individual accounting records for each project. This entails creating separate analytical accounts within the general chart of accounts so that all income, expenses, and payments associated with a specific project are recorded in a clear, easy-to-follow, and verifiable manner.

Another basic principle as described by *Azzam et al. (2020)* [7], in the accounting of non-reimbursable European funds, is a clear distinction between qualifying expenses that can be repaid from non-reimbursable European funds and ineligible ones that must be covered out of pocket. Eligible expenses are specified in the applicant's guidelines and finance contracts, and to be approved, they must be justified and incurred throughout the project's eligibility period.

In accounting, *Bachtler și Gorzelak (2007)*[8] showed that these expenses must be highlighted separately to allow their verification by the management and control authorities. Expenditures made using non-reimbursable European funding can be accounted for in two ways, depending on the nature of the project. When it comes to investments, such as the purchase of equipment or the construction of a building, the funds received are recorded as deferred income, which is not recognized as income right away but rather gradually as the financed asset depreciates. If the project is operational, the funds are recognized as current income after the eligible expenses have been incurred. All of this falls under MFP Order No. 1802/2014.

All costs incurred in a project receiving non-reimbursable European financing must be accompanied by supporting documentation, such as contracts, invoices, activity reports,

time sheets, and payment orders. Additionally, a precise record of the relationship between the activities performed and the expenses incurred must be maintained. Depending on national laws and funder regulations, all supporting documentation must be retained for a predetermined amount of time, typically five to ten years after the project is finished.

Most European programmes require the use of separate bank accounts for project-related financial transactions. This means that each project has a separate account for receiving funds and making payments, which contributes to clearer records and facilitates audit and subsequent control. Transactions in these accounts must be properly recorded in the accounts, with reference to the project to which they belong(HG 93/2016).

The determination of whether or not value added tax (VAT) is qualified for reimbursement is crucial. The VAT is deemed ineligible within the project and is not paid from European funds if the recipient is registered as a VAT payer and is able to deduct this tax. In contrast, the VAT may be deemed eligible and reimbursed by the financing if it is not deductible. This element needs to be made clear starting with the project submission phase and included in the accounting documentation.

Recipients of European subsidies are required to prepare regular financial reports that detail the project's status and provide justification for the costs spent. These reports must match the accounting data and come with requests for reimbursement or payment. Financial adjustments or even funding loss may result from irregularities or discrepancies between accounting records and financial reporting (OUG 40/2015).

Projects financed by European money may be evaluated using on-the-spot checks, financial audits, or administrative scrutiny. These are conducted by the Romanian Court of Auditors, governing authorities, state intermediary entities, or even the European Commission and European Anti-Fraud Office (OLAF). The beneficiary might have to pay back the money if there are shown to be irregularities in the accounting or unnecessary expenses. Sound financial management and compliance to national and European regulatory frameworks depend on the control, audit, and integrity of non-reimbursable external funds. They aid in avoiding mistakes, fraud, and the misappropriation of public funds. According to Figure 1, there are several types of control of non-reimbursable European funds.

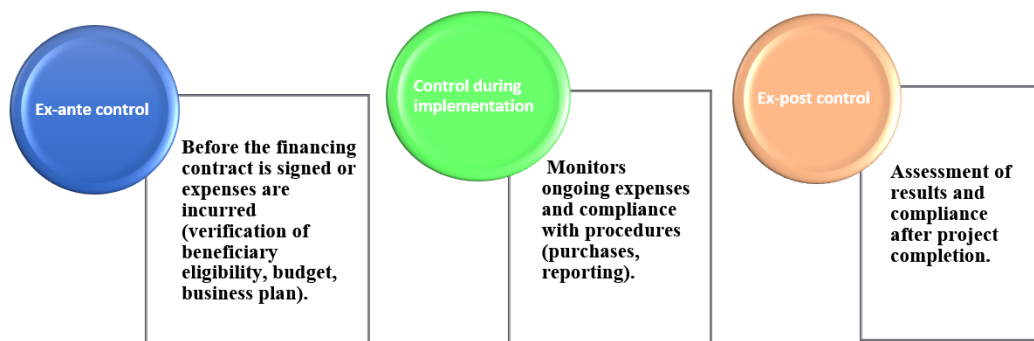


Figure 1. Types of control of non-reimbursable European funds

Source: own contribution based on the literature studied

Another important component for ensuring sound financial management and compliance with the European and national regulatory framework is auditing, which can take several forms, as shown in Figure 2.



Figure 2. Types of audit of European non-reimbursable funds

Source: own contribution based on the literature studied

The audit of European non-reimbursable funds plays an essential role in ensuring the correct, efficient and transparent management of money from the European Union budget. The audit verifies whether the funds have been used in accordance with national and European legislation, as well as with the objectives set out in the financing contract. The purpose of the audit, as stated by *Baltos et al. (2018)* [9] is to identify any anomalies, mistakes, or fraud and stop them from happening, helping to safeguard the European Union's financial interests.

An impartial and independent evaluation of beneficiaries' project and resource implementation is provided by the audit. The beneficiaries and controlling authorities receive suggestions for enhancing procedures and boosting administrative effectiveness, and the activity encourages accountability and openness in the use of public funds. As a result, the audit serves as both a control tool and an instrument to enhance institutional capacity growth and good governance (*Radu M.2012*) [10].

To ensure accurate financial management, accounting for European money necessitates a high degree of professionalism and rigor. The terms of the financing contract, the standards for the financing program, and accounting laws must all be closely adhered to by the beneficiaries. For any project funded by non-reimbursable European funds to be successful, accounting records must be properly organized, supporting documentation must be preserved, and reports must be prepared on time. Both national and European laws, as well

as the methodological guidelines unique to each funding program, must be acknowledged by beneficiaries.

5. Particulars of accounting for projects financed with non-reimbursable money

For projects funded by non-reimbursable funds, *managing supporting documentation entails gathering*, preserving, and meticulously documenting all supporting documentation for the project's declared expenses and activities in order to provide justification to the financier (the EU, the managing authority, AMPOR, etc.) and auditors.

We can state that the administration providing supporting documents is critical to transparency and eligibility, as funding may be denied without the proper documents. Both components are absolutely necessary, complementary, and must be managed properly in compliance with the applicant's guidelines and accounting legislation. To manage these processes properly, entities receiving European funds must have excellent accounting systems, well-trained staff, and very strong internal procedures. This assures not just compliance with European Union rules, but also effective and transparent administration of public resources, which is critical to the success of European Union-funded initiatives.

Peters et al. (2015) [11] discussed the European Union's criteria for acceptable supporting document formats and retention periods. The European Union requires that all papers be kept for at least *five years* after the project's completion to enable for post-implementation audits, and it emphasises the need of businesses having clear policies and precise procedures for document management and archiving.

Managing supporting documentation is just as crucial as carrying out a project. In this sense, a comprehensive, well-organized archive that is linked to accounting and technical records guarantees not only a simple verification process during monitoring/verification visits, but also the avoidance of financial corrections or reimbursements of amounts. Documents are typically arranged in physical files or digital files in PDF format, with descriptions included and the documents numbered and arranged thematically and chronologically. Document loss, incomplete or unclear scans, invoices unrelated to project activities, and non-compliance with eligibility requirements—such as improperly handled VAT or a lack of procurement procedures—are all mistakes that should be avoided.

Organizations handling European funds must put in place high-performance accounting information systems, hire skilled accounting and auditing staff, and create transparent operating procedures that are updated often in response to legislative changes in order to avoid these circumstances. The success and sustainability of projects involving non-reimbursable finance depend on the effective, transparent, and responsible management of public funds, which is ensured by meeting these standards in addition to adhering to EU legislation.

Specific accounting records in the case of projects financed by non-reimbursable European funds are accounting notes that are made separately, recorded in the accounting records, and reflect the eligible expenses incurred within a project, the rights to reimbursement of these expenses, the subsidies received from the financing authority, and asset acquisitions (if it is an investment). **Specific accounting records** clearly show the flow of money in

projects, from the beneficiary's expense to the actual collection of monies. The accounting record of European funds allocated to projects consists of numerous stages and types of particular accounting records that are required to maintain transparency, control, and compliance with legal restrictions.

The supporting documents considered essential for the management process within projects are presented in Figure 3.



Figure 3. Supporting documents for non-reimbursable financing projects

Source: own contribution based on the literature studied

6. Accounting treatment of grants and reimbursements

Azzam *et al.* (2020) [12] define European grants as non-refundable sums that are given to a public institution, non-profit organization, or PFA in order to carry out a project that has an economic, social, educational, or investment goal. The European Union provides these funding through a number of programs, including PEO, PNRR, and others, in accordance with a finance contract that outlines the terms, due dates, and categories of allowable expenses.

European grants work towards a number of strategic goals intended to promote social cohesion and sustainable development across the EU. Supporting employment via fostering social inclusion and the creation of new jobs, especially for vulnerable groups, is one of the

primary objectives. Additionally, these grants support ongoing professional development, which helps individuals adjust their skill set to meet the demands of a dynamic industry.

Additional significant goals include developing public infrastructure, particularly in impoverished areas, as well as promoting innovation and digitization in public administration, education, and the commercial sector. European subsidies are also critical for the transition to a green economy since they support initiatives that promote energy efficiency, the use of renewable energy sources, and environmental protection (Guşul, 2023)[13]. These funds help prevent climate change and support areas affected by economic transformations, such as mining regions or areas dependent on polluting industries. European grants, on the one hand, support rural development and agricultural modernization, ensuring a higher standard of living in rural areas and increasing farmer competition. Depending on the goals of financial programs, European Grants subsidies are given to a wide range of beneficiaries. With the ability to access European money for infrastructure modernization, public service digitization, or the execution of social and environmental policies, local and central public bodies are a crucial target group. Additionally, financial support is available to small and medium-sized businesses, start-ups, and social enterprises for technological development, investment, innovation, and internationalization (Dumitru et al., 2017).[14]

Within the framework of initiatives that support social inclusion, education, and labor market integration, non-governmental organizations and those offering vocational training are specifically targeted. Funding for innovation projects, global partnerships, or the updating of the material basis might be advantageous for educational and research organizations. Last but not least, in some circumstances, people can get help, especially with professional counseling, employment assistance, qualification courses, or starting their own business.

The sums obtained under contracts for non-reimbursable financing projects are made up of subsidies that can be used to pay for two main categories of expenses: investments (like buying buildings, software, equipment, or supplies) and operations expenditures (like hiring staff, buying materials, or hiring services). Romanian accounting regulations (OMFP 1802/2014 for entities applying accounting regulations in accordance with European directives or OMFP 2844/2016 for entities applying IFRS – International Financial Reporting Standards) and the guidelines set forth by the financing contracts must be followed when treating subsidies and reimbursements in the context of projects funded by European funds.

Generally speaking, *each of these sums is handled independently while adhering to the accurate representation and prudence principles*. From an accounting perspective, beneficiaries do not immediately record the pledged amount as income when they sign a financing contract with the controlling authority. The rationale is that revenue is only recognized when it is certain, that is, after the recipient has spent acceptable expenses and they have been accepted for reimbursement, in accordance with *the principle of accounting prudence*.

However, the business must keep an off-account record of the project and manage the associated documentation, including the project budget, a procurement plan, an expected estimate, and qualifying categories. After the beneficiaries have incurred the expenses, they will file a reimbursement request with the funding authorities. If this request is accepted

and the expenses are determined eligible, the beneficiaries have the right to realize the associated income in the accounting.

The recognized value will be equivalent to the amount granted by the authority for reimbursement. At the same time, a claim against the funding authority is entered in a separate account titled "*European non-reimbursable funds*". Following approval of the reimbursement request, the funding authority transfers the appropriate amount to the beneficiary's bank account.

At that point, the actual receipt of the money is documented in the accounting by deducting "*European non-reimbursable funds*" and raising "*Bank accounts in lei*".

This stage concludes the operating grant cycle; expenses have been incurred, grants have been approved, and funds have been received.

The accounting method for investment grants is different if the project involves the acquisition of machinery or other material assets. Equipment is listed as a fixed asset at the time of purchase. The amount reimbursed is not immediately recorded as income after the financing authority approves the reimbursement request; rather, it is recorded as an investment grant in the "*Investment grants*" account.

As the equipment depreciates, this sum will stay there and be progressively re-recorded in income. The investment subsidy is recognized as income proportionate to the depreciation of the funded asset rather than as income in a single installment in order to adhere to the matching expenses to income principle. As a result, the corporation will re-record a portion of the investment subsidy in income each month or year as it depreciates the equipment—that is, as it uses it and recognizes its accounting wear and tear.

The organization carrying out a project using European funding must maintain distinct accounting and extra-accounting records for every project. Clear information about the acceptable expenses incurred, their type, the amounts requested and authorized for reimbursement, and the status of the cash collected must all be included in these etc.

The relationship between the income and the expenses financed by subsidies is documented both at the end of each month when the subsidies corresponding to the expenses incurred are recorded as income and in the monthly profit and loss account, where the expenses are highlighted based on their nature. If the costs associated with subsidies have already been incurred, the receivable from subsidies is recorded in the balance sheet in line with the revenues from subsidies; if not, it is recorded on account of deferred revenues.

Additionally, subsidies are recorded on the balance sheet, and the amounts recorded as receivable from subsidies are regularized on a regular basis along with the request for reimbursement of the equivalent of the expenses incurred or based on other documents establishing and approving the amounts due (Figure 4).

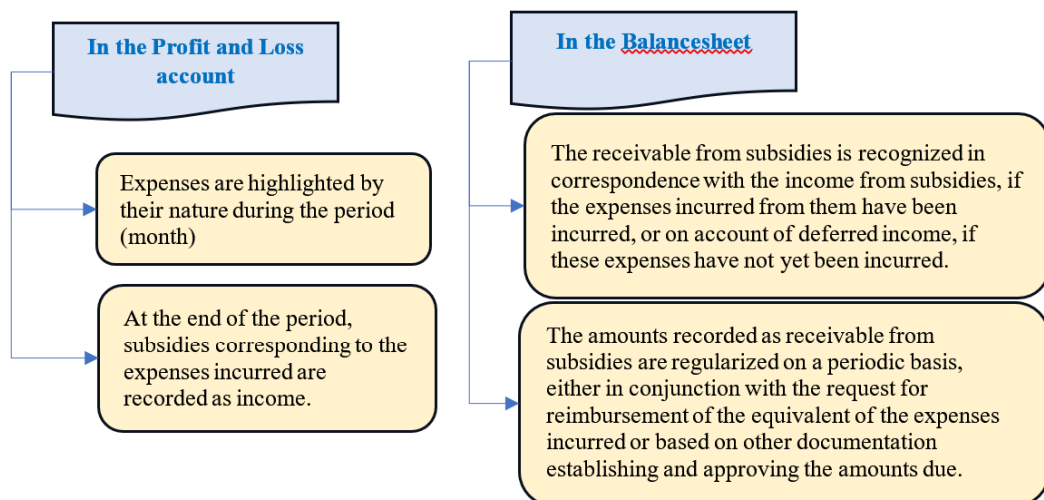


Figure 4. Presentation of grants from non-repayable external funds in the financial statements

An entity runs the danger of claiming uncertain income and making unjustified tax payments if it registers subsidies too soon, before approval. Additionally, there may be major accounting mistakes and even project financial revisions if operational and investment subsidies are not kept separate. Furthermore, in the event of an audit, unclear project records may give rise to allegations of fraud or non-compliance.

Repayment of a subsidy from European funds may take place if the recipient violates the terms of the financing agreement or utilizes the money in an inappropriate or ineligible way. This procedure, referred to as *financial rectification*, is an attempt to recoup sums that were deemed to have been spent excessively.

In actuality, amounts are corrected when irregularities are discovered after a control (executed by the managing authority, intermediate body, Court of Auditors, OLAF, or other control institutions). These irregularities may include: conflicting interests, non-compliant public procurement, expenditures without supporting documentation, disregard for the sustainability of the investment, or unapproved project modifications. A percentage adjustment (e.g., 5%, 10%, 25%, or even 100% of the value of the impacted expenditure) or a full refund of the amount issued may be requested, depending on how serious the irregularity is.

After being formally informed and given the chance to voice their opinions, the beneficiary receives a refund or compensation if the irregularity is verified. To prevent these circumstances, it is crucial that beneficiaries adhere closely to the regulations set forth in the funding guidelines and the contract, preserve all supporting documentation, and guarantee openness in the implementation process.

We can conclude that the concepts of transparency, separating eligible and ineligible expenses, and allocating subsidies *based on their usage form the foundation of the*

accounting treatment of subsidies and reimbursements within projects funded by non-reimbursable European funds.

To make future audits and verifications easier, it is crucial that all records be accurately maintained and that supporting documentation be kept on file. Sound accounting principles underpin the accounting treatment of subsidies and reimbursements for projects funded by non-reimbursable European funds. These principles **include matching subsidies with expenses and depreciation, reporting operating and investment subsidies separately, and recognizing income when certain.** Beneficiaries of these funds must work with qualified accounting professionals and adhere closely to accounting laws and funding regulations.

7. Financial reporting: rules and procedures related to projects financed from non-reimbursable funds

To guarantee the proper and effective use of public funds, *financial reporting* for projects funded by non-reimbursable European funds is a demanding and highly regulated process. This crucial field, which is governed by specific regulations meant to maximize efficacy and reduce the danger of fraud, guarantees transparency and accountability in the use of public resources.

Regular internal and external audits are also mandated by financial reporting standards; this practice not only guarantees regulatory compliance but also boosts stakeholder confidence in the appropriate handling of finances. (Magán-Maganto, et al., 2017) [15] highlighted the important role of audits in early detection of any deviations from standard reporting practices and in implementing appropriate corrective measures. In addition, compliance with reporting standards is often verified through inspections by national and European authorities, an essential aspect for ensuring the long-term financial sustainability of projects. The necessity for ongoing education and training for those involved in fund management and reporting goes hand in hand with transparency in financial reporting.

(Milward, 2009) [16] demonstrates the value of training courses that improve the particular abilities required to comprehend and implement complex financial reporting regulations. These initiatives reduce human error and improve the efficacy of the reporting process. A key component of financial management for projects funded by European funds is financial reporting, which is necessary to maintain transparency and to satisfy the EU's audit and compliance regulations. In this way, financial reporting practices are made to guarantee effective tracking of resource allocation and utilization, which promotes improved risk management and fund allocation optimization. The accomplishment of set goals and the effectiveness of project implementation are greatly influenced by accurate and timely reporting.

An essential aspect consists in the necessity of adapting reporting procedures to the details of each project, taking into account the wide range of disciplines and the various criteria of different funding programs. This requires an in-depth comprehension of financial regulations, as well as the capacity to effectively interpret and apply them. Pita et al. (2010) [17] have demonstrated that reporting systems need to be adaptable enough to enable quick modifications in the event that funding priorities or rules change.

Internal and external audit is very important for verifying compliance with financial reporting procedures. Different specialists have examined the significance of regular audits, which offer suggestions for improving reporting procedures in addition to spotting possible anomalies or deviations from financial standards. Therefore, auditors play a crucial role in guaranteeing the accuracy and legitimacy of financial data that is disclosed.

Furthermore, technology is crucial to updating and simplifying financial reporting procedures. The significance of integrated information systems that enable real-time data collecting and promote communication between management authorities and beneficiaries has been highlighted by several writers. Utilizing cutting-edge software solutions improves the accuracy of the financial data supplied by minimizing human error and expediting the reporting process.

The EU Regulations, which regulate the use of European Structural and Investment Funds, the Managing Authority's (MA) orders, which outline the specific rules applicable to each type of project or operational program, the Financing Contracts, which are signed between the fund beneficiaries and the MA and clearly outline the conditions for implementation and financial reporting, and the Guidelines for the applicant and the beneficiary, which offer more details on the eligibility requirements and the steps to be taken, provide the primary legal framework for financial reporting. The MA, the Intermediate Bodies (IBs), which may be in charge of carrying out particular programs, and national or European audit authorities, like the Court of Auditors or the DLAF (Department for the fight against fraud, DLAF is the contact institution of the European Anti-Fraud Office within the European Commission and the Anti-Fraud Coordination Service in Romania), are among the organizations involved in the management of European funds in this context.

Throughout a project's execution, a beneficiary is required to provide a variety of financial reports. These financial reports—such as intermediate and final financial reports and requests for reimbursement or payment—are crucial to ensuring that European funds are used appropriately. **MySMIS**, the online platform used by recipients of European funding to submit financial reports and reimbursement requests, is one of several online tools and platforms that make managing and submitting documents easier in the financial reporting processes. In Romania, this is used for most of operational programs. As resources that make document management and submission easier, we think of the Managing Authority's Guides and Manuals, which outline the required and necessary steps for financial reporting and offer crucial details on the kinds of expenses that qualify, the documents that are needed, and the protocols that must be followed within a project's execution. The proper implementation of projects and the ability of beneficiaries to reimburse qualified expenses are ensured by following the regulations and protocols set forth by national and European authorities.

It is critical that all expenditures are supported by explicit supporting papers, that contractual terms and public procurement procedures are followed, and that recipients are transparent and in compliance with EU and national regulations. Common errors, such as document discrepancies or invalid expenditure, can result in sanctions or even financial loss, thus each stage of the reporting process must be properly reviewed and followed.

8. Conclusions

The accounting of European non-reimbursable funds is a critical component in ensuring effective, transparent, and compliant administration of allowed financial resources in compliance with national and European legislation. The entire process, from documenting accounting operations to limiting eligible expenses, processing subsidies and reimbursements, maintaining supporting papers, and conducting audits, is rigorously controlled and requires a high level of professionalism and precision.

Compliance with the regulatory framework, proper application of accounting principles, and keeping of clear and distinct records for each project, all contribute significantly to its success and sustainability by preventing errors, financial adjustments, or financial losses. As a result, accounting is more than just a legal necessity; it is also a strategic tool for financial management, internal control, and responsibility in the use of European public funds.

The intricate nature of the legal framework governing the accounting of projects with non-reimbursable financing is highlighted, beginning with European regulations (Regulation 2021/1060, Financial Regulation 2018/1046) and continuing with national legislation (Accounting Law no. 82/1991, republished, OMFP 1802/2014 for entities applying accounting regulations in accordance with European directives or OMFP 2844/2016 for entities applying IFRS - International Financial Reporting Standards, OMFP no. 1917/2005 for public institutions).

It also emphasizes the importance of auditing, supporting documentation, and rigorous financial flow management in confirming expenditures and avoiding financial corrections. Accounting, in this environment, becomes more than just a recording tool; it is a critical pillar of transparency, compliance, and project success when funded with non-reimbursable funds.

The role of accounting in the management of projects financed from European funds goes beyond the framework of a system for recording financial flows and becomes a mechanism for controlling, reporting, monitoring and preventing risks in the implementation of projects. A well-structured accounting record provides the beneficiary with a clear picture of cash flows, expenditure by category, own contribution and non-reimbursable financing and the degree of absorption of funds in a timely manner.

Cost management is an essential component of project management, recognized as one of the most critical dimensions for achieving the proposed objectives. Both the specialized literature and management practices indicate that accurate accounting and rigorous cost control not only maximize the efficient use of financial resources but also reinforce the sustainability of the projects implemented. In the case of non-reimbursable projects, the additional complexity generated by compliance with eligibility, reporting, and audit requirements necessitates increased attention to the way costs are planned, monitored, and controlled. The temporary nature and specific objectives of non-reimbursable projects require adapted accounting and a management capacity focused on quantifiable results.

In the context of growing global economic and geopolitical uncertainties, as well as the 2021–2027 financial programming at European Union level, which emphasizes greater responsibility of beneficiaries in managing funds, the adoption of appropriate cost management practices becomes essential to reduce the risks of non-compliance, loss of funding, or failure to achieve the proposed results.

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