JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT

JISOM
VOL.20 NO.1
MAY 2026

ROMANIAN-AMERICAN UNIVERSITY

ANALYZE, CREATE, SHARE KNOWLEDGE

JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT

VOL. 20 NO. 1

MAY 2026

ROMANIAN-AMERICAN UNIVERSITY PUBLISHING HOUSE
BUCHAREST

EDITOR-IN-CHIEF NOTE

JISOM is a journal which enables researchers, academia, and professionals to make their voices heard, to share their findings with their peers and the public at large. Being an open-access journal, JISOM aims to increase the all-around level of knowledge in the fields of computer science and economics, to further the society's capabilities to understand new concepts, to see how things are done by cutting-edge technologies implementations, to understand what is in store for us not only at the present time but also in the near, and so near, future.

The published articles focus mainly on IT&C but we also provide a favorable exposure medium for correlated topics, such as economics, management, applied sciences, mathematics, statistics, etc. JISOM encourages cross-disciplinary research of national and international researchers and welcomes the contributions which give new and fresh perspectives to the above-mentioned fields of study.

National and international researchers, professionals, recognized experts, professors who want to share their research results and new ideas, and Ph.D. students who want to improve their knowledge or present their emerging doctoral research are all welcome to join our knowledge-eager community.

We have a history that started back in 2007 and we are permanently striving to bring our community to a higher level of knowledge in the fields we cover. With the constant support of our authors, reviewers, readers, and editorial staff I am sure we are and will live up to the mission we have taken on.

Many thanks to our JISOM community and good luck with your research!

Respectfully,

Alexandru TĂBUȘCĂ, PhD

JISOM Editor-in-Chief

JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT

EDITOR-IN-CHIEF

Alexandru TĂBUȘCĂ, PhD Associate Professor

MANAGING EDITOR

Daniela Alexandra CRIȘAN, PhD Associate Professor

EDITORIAL BOARD

Academician Gheorghe Păun	Romanian Academy, Romania
Professor Alexandru Pîrjan	Romanian-American University, Romania
Professor Allan Berg	University of Dallas, USA
Professor Cornelia Botezatu	Romanian-American University, Romania
Professor Costin Boiangiu	Politehnica University, Bucharest, Romania
Professor Carlos Rompante da Cunha	Bragança Polytechnic University, Portugal
Professor Cristina Coculescu	Romanian-American University, Romania
Professor Eduard Rădăceanu	Romanian Technical Academy, Romania
Professor George Căruțașu	Romanian-American University, Romania
Professor Ion Ivan	Academy of Economic Studies, Romania
Professor Ion Smeureanu	Academy of Economic Studies, Romania
Professor Kent Zimmerman	James Madison University, USA
Professor Lucia Rusu	Babes-Bolyai University, Romania
Professor Pauline Cushman	James Madison University, USA
Professor Ramon Mata-Toledo	James Madison University, USA
Professor Sergiu Iliescu	Politehnica University, Bucharest, Romania
Professor Traian Muntean	Universite Aix–Marseille II, France
Professor Victor Patriciu	National Technical Defence University, Romania
Professor Viorel Marinescu	Technical Civil Engineering, Romania
Associate Professor Alexandru Tăbușcă	Romanian-American University, Romania
Associate Professor Daniela Alexandra Crișan	Romanian-American University, Romania
Associate Professor Irina Făgărășanu	Politehnica University, Bucharest, Romania
Associate Professor Mihaela Păun	Louisiana Tech University, USA
Associate Professor Sanda Micula	Babes-Bolyai University, Romania
Associate Professor Susan Kruc	James Madison University, USA

Senior Staff Text Processing:

Lecturer Gabriel Eugen Garais	Romanian-American University
Lecturer Justina Lavinia Stănică	Romanian-American University

JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT

Journal details

No.	Item	Value
1	Complete title / IDB title	JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT
2	ISSN (print and/or electronic)	1843-4711
3	Frequency	semestrial
4	Journal website (direct link to journal section)	http://jisom.rau.ro
5	IDB indexation	EBSCO GALE Cengage Learning Index Copernicus ProQuest RePEC/IDEAS

Contact

First name and last name	Alexandru TĂBUŞCĂ, PhD Associate Professor
Phone	+4-0372-120.140
E-mail	alex.tabusca@rau.ro

ISSN: 1843-4711

TABLE OF CONTENTS

THE EVOLUTION OF THE SEMANTIC WEB: FROM FOUNDATIONAL TRIPLES TO THE AGENTIC ERA 1

ADAM ALTĂR – SAMUEL
DANIELA ALEXANDRA CRIȘAN
JUSTINA LAVINIA STĂNICĂ

CHANGES IN LEGAL PROFESSION BROUGHT BY AI AND THEIR INTEGRATION IN SERBIAN PRACTICE 17

UROS ATANASKOVIC
ALEXANDROS KAPOULAS
IVANA NIKOLIC
SRDJAN NIKOLIC

THE IMPACT OF DIGITALIZATION AND AUTOMATION ON THE ACCOUNTING PROFFESION IN ROMANIA: A QUALITATIVE STUDY 41

LUCIAN – COSMIN BĂDĂLĂU
GEORGIANA - JANINA SOARE

ADAPTIVE MULTI-OBJECTIVE OPTIMIZATION OF DEEP GROOVE BALL BEARINGS FOR HYDROGEN COMPRESSOR APPLICATIONS USING DYNAMIC CROSSOVER AND MUTATION PROBABILITIES 62

PRASUN BHATTACHARJEE
SOMENATH BHATTACHARYA

GAMIFICATION STRATEGIES TO INCREASE EMPLOYEE ENGAGEMENT INTO SUSTAINABILITY 79

CODRUȚ FLORIN CRĂCIUN
PAUL-TIBERIUS COMAN
OANA PREDA
NICOLETA ROSSELA DUMITRU

LABOUR MIGRATION IN ROMANIA: CURRENT TRENDS AND CHALLENGES FOR 2026 97

ELENA RALUCA CRISTIAN
LAURA GEORGETA BĂRĂGAN

ANALYSIS OF THE STUDENT DEFICIT IN TOURISM SPECIALIZATIONS IN ROMANIA 115

GINA GILET (LEFTER) DOBROTĂ
EMILIA GABROVEANU

AI-BASED HOMEWORK ASSISTANCE AS A SERVICE INNOVATION IN PRIVATE EDUCATION: OPPORTUNITIES, PERCEIVED VALUE AND EXPECTED LEARNING OUTCOMES 134

CRISTINA DRAGAN

SMART RAPID-DEPLOY MODULAR HOUSING AS URBAN RESILIENCE INFRASTRUCTURE - A PATENT-INFORMED FRAMEWORK FOR CONNECTED SMART CITIES 153

EUGEN GABRIEL GARAIS

AN EXPERIMENTAL AGENT-BASED CITY SIMULATION: PERSONALITY-DRIVEN ECONOMIC BEHAVIOR AND STABILITY OUTCOMES 165

BOGDAN-GABRIEL GHEORGHE

INTELLIGENCE-ENABLED SUSTAINABLE MARKETING IN SDG-DRIVEN MARKETS: INTEGRATING DIGITAL TRANSFORMATION, COMPETITIVE INTELLIGENCE, AND ORGANIZATIONAL CONSCIOUSNESS 180

CEZARA M. GIUGULA
DANIEL G. DINU

NAVIGATING ANNUAL FINANCIAL REPORTING IN EUROPEAN SINGLE ELECTRONIC FORMAT (ESEF): A GUIDE FOR EU-LISTED COMPANIES 200

COSMIN IONUȚ LUNGU

THE EVOLUTION OF SOFTWARE PROJECT MANAGEMENT REGARDING QUALITY AND SUCCESS 212

LUCA TEODOR MÂNDRU
ANDREI RADU COJOCARU
ALEXANDRA BURNICHI
COSTIN ANDREI VLAD
COSTIN-ANTON BOIANGIU
NICOLAE TARBĂ

THE TRADE-OFF BETWEEN PERFORMANCE, COST AND ENVIRONMENT IMPACT IN SOFTWARE DEVELOPMENT 231

ANDREI NĂPRUIU
FLAVIUS PETRACHE
LARISA ELENA FLOREA
ȘTEFANIA MARIA FÎNTÎNĂ
MĂDĂLINA-ELENA TIȚA
COSTIN-ANTON BOIANGIU

DIGITAL BOOKING PLATFORMS AND INBOUND TOURISM PERFORMANCE: EVIDENCE FROM EU COUNTRIES 266

IOANA C. PATRICHI
PATRICIA S. DODU

THE IMPACT OF AGENTIC CODING ON THE MODERN SOFTWARE DEVELOPMENT LIFECYCLE 285

ALEXANDRU PÎRJAN
DANA-MIHAELA PETROȘANU

THE IMPACT OF AI-ASSISTED DEVELOPMENT ON THE PRODUCTIVITY OF SOFTWARE TEAMS 326

TEODORA POPESCU
STEFANIA GRECU
ANDREEA-GEORGIANA GRIGOREANU

ANA-MARIA PERȘENEA
COSTIN-ANTON BOIANGIU

ANALYSIS OF ONLINE PURCHASING BEHAVIOR AND ONLINE SUPERMARKET USAGE AMONG YOUNG ADULTS 346

TAKUNE SAKAUE
NOBUTAKA SUZUKI

INTEGRATION OF ARTIFICIAL INTELLIGENCE IN THE INTERNAL MANAGERIAL CONTROL OF EDUCATIONAL INSTITUTIONS AND IMPLICATIONS ON INTERNAL AUDIT 361

GEORGIANA JANINA SOARE

RESHAPING NONVERBAL COMMUNICATION IN A BUSINESS ENVIRONMENT RULED BY VIRTUAL MEETINGS 385

GEORGIANA SURDU
VALERIU POTECEA

GLOBAL DISRUPTIONS AND THEIR IMPACT ON INTERNATIONAL LOGISTICS .. 398

GEORGIANA SURDU
VALERIU POTECEA
GHEORGHE CARAIANI

DIGITALIZATION STRUCTURALLY CHANGES THE LABOUR MARKET: A COMPARATIVE ANALYSIS IN EU COUNTRIES 413

ALEXANDRU TĂBUȘCĂ
ALEXANDRA HOSSZU
MIHAI ALEXANDRU BOTEZATU
ANDREI LUCHICI
SILVIA TĂBUȘCĂ
ALEXANDRU ENĂCEANU
DRAGOȘ-PAUL POP

EUROPEAN DIGITAL LEGISLATION 2026: A LANDMARK YEAR FOR THE EUROPEAN DIGITAL GOVERNANCE FRAMEWORK 452

ALEXANDRU TĂBUȘCĂ
SILVIA TĂBUȘCĂ

MODELING THE FLOW OF RESOURCES IN A BALANCED ECONOMIC SYSTEM: FROM A KEYNESIAN PERSPECTIVE 470

CARMEN DALINA ȚÎRDĂ
ELENA RALUCA CRISTIAN
ANDA VERONICA DAN

ARTISTICALLY ENHANCED IMAGES: A STUDY ON ACCESSIBILITY AND CREATIVE STYLE IN VIDEO GAMES 489

MIHAI-LUCIAN VONCILĂ
EREN MURAT
DRAGOȘ-BOGDAN TUDOR
IOAN-LICĂ MARIN
MIHAI UDUBAȘA
OANA IRINA TURCU
NICOLAE TARBĂ

COSTIN-ANTON BOIANGIU

CLUSTER ANALYSIS ON THE USE OF GENERATIVE AI TOOLS BY INDIVIDUALS IN EUROPEAN UNION CONTRIES 510

MARIAN ZAHARIA
CAMELIA-MONICA GHEORGHE

ACCOUNTING-FINANCIAL ANALYSIS: AN AMPLIFYING FACTOR IN FINANCIAL REPORTING KNOWLEDGE GROWTH 533

MARILENA ROXANA ZUCA

FINANCIAL AUDIT BETWEEN ACCOUNTING ACCURACY AND THE VALIDATION OF THE TRUE AND FAIR VIEW 558

MARILENA ZUCA
ALICE EMILIA ȚÎNȚA
ANDA MIHAELA LĂCEANU
GEORGIANA POPA

THE EVOLUTION OF THE SEMANTIC WEB: FROM FOUNDATIONAL TRIPLES TO THE AGENTIC ERA

Adam ALTĂR – SAMUEL[1]
Daniela Alexandra CRIȘAN[2]
Justina Lavinia STĂNICĂ[3]

Abstract

This paper analyzes the evolution of the Semantic Web into the "Agentic Web", a digital ecosystem designed for autonomous AI agents. This transformation is driven by advanced W3C standards like RDF 1.2, which introduces triple terms to streamline complex metadata management and optimize graph storage. A critical focus of the research is the neuro-symbolic integration of these structured knowledge graphs with Large Language Models (LLMs) to mitigate AI hallucinations and enable accurate reasoning. Additionally, the paper explores how the emerging Web Model Context Protocol allows traditional websites to expose structured, agent-ready tools natively in the browser. Finally, it examines the necessity of Decentralized Identifiers and Verifiable Credentials, which provide a cryptographic trust layer enabling AI agents to securely authenticate, negotiate, and transact across different domains without requiring constant human oversight.

Keywords: Semantic Web, Agentic AI, Knowledge Graphs, Large Language Models (LLMs), Web Model Context Protocol (WebMCP)

JEL Classification: L86

1. Introduction

The conceptualization of the World Wide Web fundamentally transformed global communication by interlinking documents to facilitate human consumption and knowledge sharing. However, the sheer volume, rapid expansion, and unstructured nature of these digital documents necessitated the development of a parallel architecture—one designed explicitly for machine interpretation rather than human reading. This parallel architecture,

[1] PhD, Associate Professor; Department of Computer Science, Mathematics and Statistics; Romanian – American University, Bucharest, Romania; adam.altar@rau.ro
[2] PhD, Associate Professor; Department of Computer Science, Mathematics and Statistics; Romanian – American University, Bucharest, Romania; daniela.alexandra.crisan@rau.ro
[3] PhD, Lecturer; Department of Computer Science, Mathematics and Statistics; Romanian – American University, Bucharest, Romania; lavinia.stanica@rau.ro

known historically and presently as the Semantic Web, was introduced to endow digital information with well-defined meaning, enabling computers and software agents to process, integrate, search, and act upon data autonomously across vast networks [1].

In its earliest iterations, the Semantic Web was viewed primarily as an engineering solution constructed utilizing Uniform Resource Identifier (URI) syntax and the Extensible Markup Language (XML) to standardize the transmission of machine-understandable data [1]. By the year 2026, this academic framework has matured into the critical, structural backbone powering global artificial intelligence systems. The global semantic knowledge graphing market has reached an estimated valuation of $4.9 billion in 2026, with financial projections indicating a surge to $15.2 billion by the year 2033, driven by a compound annual growth rate (CAGR) of 17.6%. Furthermore, the broader semantic web market, encompassing data integration tools and inference engines, is projected to reach $7.73 billion by 2030, scaling at a CAGR of 23.3%.

This rapid expansion is primarily catalyzed by the critical necessity for structured semantic data to support the contextual understanding required by modern Large Language Models (LLMs) and autonomous AI agents [2]. The contemporary Semantic Web is no longer merely a theoretical complement to the existing web of HTML documents; it is the fundamental infrastructure of the "Agentic Web"—an emerging digital ecosystem where intelligent, autonomous software agents handle complex tasks, orchestrate multi-step workflows, negotiate with external services, and transact securely on behalf of human users and enterprise organizations [1].

2. The Evolution of the Foundational Data Model: RDF 1.2 and Triple Terms

The Resource Description Framework (RDF) has long served as the standard data model for interchange on the Web. The core utility of RDF lies in its ability to facilitate data merging and integration even when the underlying schemas of disparate databases differ significantly [1]. Historically, RDF extended the standard linking structure of the Web by utilizing URIs to name the relationships between entities, thereby forming a directed, labeled graph [1]. Within this graph, the edges represent the named links, and the nodes represent the resources. The fundamental unit of this model is the "triple," consisting of a subject, a predicate, and an object [1].

While the triple model provided a mathematically elegant way to represent structured and semi-structured data, the limitations of the RDF 1.1 specification became increasingly apparent as enterprise knowledge graphs grew more complex. Specifically, data architects encountered severe structural inefficiencies when attempting to express metadata about the data itself—such as the provenance of a statement, certainty scores, temporal restrictions, or the specific agent that generated a fact [3]. Under the RDF 1.1 standard, the process of "reification"—expressing an abstract construct with existing concrete methods—required stating four additional triples just to refer to the single target triple for which metadata was

being provided [3]. The subject of these four additional triples required a new identifier, such as a blank node or a new Internationalized Resource Identifier (IRI).

This standard reification approach, while compliant with early specifications, created massive inefficiencies related to persisting and exchanging RDF data [3]. A database containing a billion facts could easily balloon to five billion triples simply by adding basic provenance metadata. Alternative modeling workarounds emerged, such as singleton properties, named graphs, and N-ary relations, but these approaches either increased ontology complexity to unsustainable levels or severely degraded querying efficiency by requiring complex regular expression parsing [4].

In 2026, the World Wide Web Consortium (W3C) successfully addressed these historical structural limitations through the ratification and deployment of the comprehensive RDF 1. 2 specifications [5]. The most transformative and widely anticipated feature of the RDF 1.2 data model is the formal integration of "triple terms," a concept heavily incubated in earlier years under the moniker RDF-star [5]. This advancement introduces a fourth kind of RDF term to the abstract syntax, seamlessly allowing an entire RDF triple to be utilized as the subject or the object of another triple [5]. By doing so, the framework natively enables systems to make statements about other statements without the bloat of legacy reification.

The update to the RDF 1.2 abstract data model is accompanied by critical revisions to the concrete serialization formats utilized by developers. The RDF 1.2 Turtle specification introduces highly refined syntactic sugar to make data modeling exponentially more expressive and concise [6]. The specification formally standardizes the <<(?s?p?o)>> syntax for explicitly defining quoted triple terms [6]. More importantly, it introduces a dedicated annotation syntax, represented by {|... |}, which allows triple terms to be concurrently asserted and annotated [6]. This allows data modelers to state a fact and immediately attach metadata to it within a single, highly readable block of code.

Beyond reification, the W3C RDF & SPARQL Working Group introduced several other vital enhancements. RDF 1.2 introduces directional language-tagged strings, establishing a base direction component that dictates the initial text direction for proper presentation by global user agents [5]. To manage the interoperability transition between legacy enterprise data and modern infrastructures, RDF 1.2 documents now utilize a formal version announcement mechanism, prominently featuring the VERSION "1.2" directive at the head of serialization files [6]. This ensures backward compatibility, defining precise syntax conformance boundaries so that data conforming to version "1.1" remains valid as data with version "1.2-basic" [5].

3. Advanced Query Mechanics: SPARQL 1.2 and Entailment Regimes

Because the Semantic Web represents abstract concepts in the form of triplets interconnected within a massive, directed graph, traditional relational database query languages, such as SQL, possess limited and highly inflexible syntaxes for traversing this

data [1]. The SPARQL Protocol and RDF Query Language emerged to solve this problem, acting as the fundamental mechanism for retrieving and manipulating data stored in the Resource Description Framework format [1].

A mathematically sound RDF query language must adhere to five distinct properties to function effectively at enterprise scale: expressiveness (providing relational completeness), closure (ensuring operations on a graph data model return graph data models), adequacy (utilizing all underlying concepts of the data model), orthogonality (ensuring operations are independent of their usage context), and safety (guaranteeing that syntactically correct queries return a finite set of results from finite data sets) [7].

To parallel the structural evolution of the RDF 1.2 data model, the W3C formalized the SPARQL 1.2 specification. SPARQL 1.2 expands upon the foundational SELECT, ASK, DESCRIBE, and CONSTRUCT query forms established in previous versions [1]. The primary directive of SPARQL 1.2 is to safely integrate the querying of the newly introduced triple terms while strictly maintaining the mathematical closure and safety of the graph data model.

To achieve this, the SPARQL 1.2 grammar introduces a suite of specific functions dedicated to manipulating, validating, and extracting components from triple terms. These built-in query functions include TRIPLE, isTRIPLE, SUBJECT, PREDICATE, and OBJECT. This programmatic access allows query execution engines to dissect nested metadata statements natively. In previous architectures, extracting the subject of a reified node required cumbersome graph traversal workarounds; in 2026, a developer can simply query the nested object directly. Additionally, the query language incorporates specific functions related to the new language tags and base directions, namely LANGDIR, hasLANGDIR, and STRLANGDIR, ensuring full coverage of the RDF 1.2 data model.

Furthermore, SPARQL 1.2 significantly updates the Entailment Regimes. Entailment rules are fundamental to the Semantic Web, as they state which implicit information can be logically inferred from explicit information present in the graph [1]. The SPARQL 1.2 Entailment Regimes specification ensures that basic graph pattern matching incorporates standard semantic web entailment relations without breaking the query engine. These regimes include RDF entailment, RDFS entailment, D-entailment, OWL Direct Semantics, and RIF Core entailment. This capability is absolutely critical for deep reasoning engines that must distinguish implicit logical taxonomies from explicit data declarations in real-time, allowing an AI agent to deduce that if an entity is defined as a "Pediatrician," it implicitly belongs to the broader class of "Physician," even if that specific triple is absent from the database.

Federated queries, historically orchestrated via the SERVICE keyword to merge data distributed across the Web, have also been refined. The SPARQL 1.2 Federated Query extension is designed to handle distributed query execution involving the new triple terms and updated entailments, ensuring that linked open data endpoints

can communicate complex metadata structures securely and efficiently. Software implementations, such as the open-source Oxigraph, have rapidly adopted these standards, offering stable support for SPARQL 1.2 updates, experimental operators like LATERAL joins, and advanced property path matching [8].

4. Bridging Relational Silos: The Modern RDB2RDF Mapping Ecosystem

Despite the inherent architectural advantages of native graph storage and semantic triples, the overwhelming majority of global enterprise data continues to reside in traditional Relational Database Management Systems (RDBMS). Exposing this highly structured, tabular data to the Semantic Web requires an extensive conversion process known as RDB-to-RDF mapping [1]. This process bridges the conceptual gap between relational tables (featuring primary keys, foreign keys, and rows) and the directed graphs of the Semantic Web, allowing legacy data to be seamlessly queried via SPARQL [1].

In the early developmental stages of the Semantic Web, data integration relied on rudimentary tools. Direct mapping was often executed through platforms like Virtuoso, the D2RQ Platform, and Spyder [1]. The D2RQ Platform, for example, offered a system for accessing relational databases as virtual, read-only RDF graphs without replicating the data into a dedicated RDF store, translating SPARQL queries into SQL on the fly. Spyder served as a free, less business-oriented alternative focusing exclusively on direct mapping via early W3C standards [1].

However, by 2026, the mapping ecosystem has undergone a massive, high-performance architectural shift, rendering legacy tools like Spyder and the original D2RQ framework effectively obsolete. The industry has definitively standardized around the W3C RDB2RDF Mapping Language (R2RML) and its highly flexible extension, the RDF Mapping Language (RML). RML extends the capabilities of R2RML to accommodate heterogeneous data sources beyond relational databases, including CSV, JSON, and XML documents.

The contemporary landscape of data mapping is bifurcated into two primary architectural paradigms: Virtual Knowledge Graphs (VKG) and Materialized Knowledge Graphs.

The Virtual Knowledge Graph paradigm is championed predominantly by systems like Ontop. Ontop provides a semantic abstraction layer that entirely hides complex, underlying SQL join logic behind a pristine conceptual ontology. End-users and AI agents interact with the conceptual model using SPARQL, while Ontop dynamically translates these semantic queries into highly optimized SQL, leveraging the underlying relational database's existing execution engine without ever duplicating the data. This is particularly vital for organizations with strict data residency requirements.

Conversely, for architectures requiring deep, multi-hop graph analytics, machine learning training, or high-speed LLM Retrieval-Augmented Generation (RAG) pipelines, materialized knowledge graph construction is preferred. In this space, highly scalable

mapping engines like SDM-RDFizer and Morph-KGC dominate the 2026 landscape [9]. These engines are engineered to execute RML rules to generate high-quality linked data at unprecedented scales. SDM-RDFizer addresses the immense memory storage problems of graph creation by introducing TriplesMap Planning (TMP) to define optimized execution evaluation plans, alongside novel operators for compressing data structures in memory [10]. Morph-KGC similarly achieves scale through sophisticated mapping partitions [9].

Once these massive graphs are physically materialized via ETL pipelines, they are typically hosted in enterprise-grade native cloud platforms. Amazon Neptune, for example, has become a foundational infrastructure piece, seamlessly supporting both property graph models and RDF graphs within the same managed instance, providing automated backups, point-in-time recovery, and deep integration with cloud security identity frameworks [11].

5. The Symbiosis of Ontologies and Large Language Models

Ontologies remain the conceptual bedrock of the Semantic Web. Defined philosophically as the metaphysical study of the nature of being and existence, in digital ecosystems, an ontology represents a formal file that defines relationships, classes, taxonomies, and strict rules of inference between terms within a specific domain [1]. By setting properties for specific overarching classes—with subclasses subsequently inheriting those properties—and applying inference rules, software applications can definitively deduce relationships that are not explicitly stated within the database [1]. The Protégé application, historically recognized as the most flexible ontology editor incorporating Semantic Web requirements [1], has evolved heavily into WebProtégé, integrating directly with the Ontology-Development Kit (ODK) to provide automated support, testing, and continuous integration via GitHub pipelines.

However, the utility and visibility of ontologies have expanded dramatically in 2026 due to the absolute ubiquity of Large Language Models (LLMs). LLMs, built upon advanced Transformer neural network architectures, excel at probabilistic word prediction, contextual language generation, and long-form reasoning based on the unsupervised ingestion of massive pretraining datasets. Yet, despite their linguistic fluency, isolated LLMs fundamentally lack deterministic mechanisms for factual verification, inevitably leading to "hallucinations" and severe logical inconsistencies [12].

The critical integration of Semantic Web technologies with LLMs forms a hybrid, neuro-symbolic architecture that defines modern AI. Knowledge graphs provide the definitive truth and transparency layer that probabilistic language models natively lack. By strictly grounding LLMs in highly curated, ontology-driven knowledge graphs—a sophisticated enterprise process currently known as Context Engineering or GraphRAG—organizations generate conversational AI interfaces that are structurally bound to factual, proprietary data.

This symbiosis forms a bidirectional relationship that effectively bridges the gap between structured databases and unstructured content. On one side, autonomous AI agents are

continuously deployed to ingest raw, legacy text documents, images, and audio, utilizing advanced natural language processing to automatically extract entities and relationships. The AI converts this unstructured data into perfectly formatted RDF triples, effectively automating the continuous population and maintenance of the knowledge graph.

On the other side, the semantic layer allows LLMs to engage in far more complex, multi-hop reasoning, providing highly explainable, plain-language answers to end-users. Because the semantic layer (often utilizing Virtual Knowledge Graphs) maintains strict access controls and data entitlements, the AI can securely retrieve customized answers based on the user's specific organizational role. Open structured data repositories, most notably Wikidata, serve as massive, collaboratively maintained baseline ontologies that provide high-quality training and reference data for these global AI systems, reflecting global diversity and factual transparency.

6. Semantic Search: Beyond Keyword Matching and the "Zero-Click" Paradigm

The maturation of semantic semantics and knowledge graphs has completely restructured the digital search landscape. Historically, traditional search engines relied almost exclusively on keyword density matching and reverse-indexing HTML documents. This approach was highly inefficient, often returning massive volumes of irrelevant pages because the system lacked any contextual awareness of the query's actual meaning [1]. Semantic search, conversely, focuses on comprehending the deeper intent, contextual meaning, and entity relationships behind a user's query [13].

By 2026, semantic search definitively represents the leading application type within the semantic knowledge graphing market, driven heavily by adoption rates scaling rapidly to address contextual results. Instead of matching literal character strings, semantic search engines utilize advanced NLP, vector embeddings, and entity mapping to understand the relationship between words and broader concepts. For example, an enterprise query regarding "hardware for graphic design" will retrieve entities semantically mapped to high RAM constraints and specific graphical processing capabilities, rather than blindly returning pages that simply contain the words "hardware" and "design" [13].

In complex enterprise environments, semantic search platforms seamlessly map conceptual relationships across highly dispersed data repositories (ranging from legacy codebases to HR policies), ensuring that results are highly tailored to the specific needs and permissions of the user [14].

On the public web, this technological evolution has led to an existential paradigm shift in Search Engine Optimization (SEO) and digital marketing. The traditional "10 blue links" format that defined the early web has been largely superseded by AI-driven Answer Engines [14]. This has precipitated the critical "Zero-Click" tipping point—a macroscopic reality where a vast majority of user queries are satisfied instantly by an AI synthesis of semantic

data directly on the search results page, without the user ever requiring a click-through to a third-party website [15].

Consequently, digital visibility and website growth in 2026 rely significantly less on legacy keyword density strategies and almost entirely on the robust deployment of structured schema markup and JSON-LD. By providing machine-readable, RDF-compliant semantic contracts, organizations ensure that their data, product inventory, and services are legible and highly ranked by AI crawlers and autonomous answer engines [16].

7. The Evolution of Web Services: From SOAP to the Agentic Protocols

In the early architectural designs of the Semantic Web, traditional Web services provided the primary methods for software programs to exchange data and invoke remote operations across distributed networks. The absolute dominant protocols of that era were the Simple Object Access Protocol (SOAP) for messaging, the Web Services Description Language (WSDL) for precise interface description, and Universal Description, Discovery, and Integration (UDDI) for publishing and maintaining service registries [1].

By 2026, this legacy architecture has been fundamentally overhauled to support modern web velocities. UDDI is entirely obsolete, having been initially replaced by lighter discovery mechanisms and eventually fully superseded by robust, centralized API gateways and service meshes [17]. SOAP and WSDL, while historically valued for their strict, XML-based contract-first security models, have been largely deprecated in favor of agile, lightweight frameworks [17].

The software industry transitioned heavily to Representational State Transfer (REST) APIs, an architectural style that utilizes lightweight JSON formats, standard HTTP verbs (GET, POST, PUT, DELETE), and mandates stateless communication. Concurrently, GraphQL emerged as a highly powerful, query-based API architecture. GraphQL resolved REST's inherent over-fetching issues by allowing client applications to request highly specific, complex data structures via a single endpoint, heavily utilized in front-end-driven or data-heavy mobile applications.

However, traditional REST and GraphQL APIs were fundamentally designed for human developers building applications for human end-users. As the Semantic Web transitioned deeply into the Agentic Web—an ecosystem where autonomous AI agents must execute tasks across disparate digital systems—new, machine-first protocols were urgently required [2].

Initially, AI agents interacted with the web through highly inefficient visual screen scraping or brittle Document Object Model (DOM) manipulation. The agents were forced to guess the functionality of HTML elements designed for human eyes, leading to extreme latency, high token expenditure, and high error rates.

To definitively solve this interoperability crisis, the W3C Web Machine Learning

Community Group introduced the Web Model Context Protocol (WebMCP) in early 2026. WebMCP effectively bridges the final gap between semantic data schemas and executable AI logic. It allows web applications to natively expose client-side JavaScript functions as structured "tools" to AI agents directly through the browser.

Instead of an AI agent attempting to visually parse a complex HTML calendar to book a flight, a website utilizing WebMCP declares a mathematically rigorous, natural-language described schema defining exactly how the flight-booking function operates. The agent can discover, negotiate, and seamlessly invoke these tools instantly, while securely inheriting the human user's session authorization and exact permission boundaries. This protocol definitively shifts the internet from a human-readable visual interface to an Agent-Ready ecosystem, where capabilities are semantically declared and universally actionable by machine consumers.

Furthermore, decentralized technologies like the Hydra ecosystem have reached maturity. Hydra builds entirely upon JSON-LD (JavaScript Object Notation for Linked Data) to create truly self-describing REST APIs. By embedding a semantic vocabulary directly into the API responses, Hydra enables smart clients and autonomous AI agents to discover new capabilities and traverse complex APIs dynamically without requiring hard-coded client logic, fulfilling the original Semantic Web promise of autonomous service discovery and execution.

8. The Trust Layer: Decentralized Identifiers and Verifiable Credentials

A critical, indispensable component of a functional, autonomous Semantic Web is the establishment of verifiable trust. In earlier frameworks, digital signatures—encrypted data packets ensuring a source's authenticity—were the primary mechanism by which software agents verified transactions and guarded against malicious actors [1]. However, centralized certificate authorities and isolated trust registries presented systemic vulnerabilities, friction, and privacy concerns.

By 2026, the absolute necessity for robust, scalable digital trust—driven by heavy regulatory pressures and massive enterprise demand for fraud-proof identity management—has led to the widespread adoption of Decentralized Identity frameworks. The foundation of this new semantic trust layer relies entirely on open W3C standards for Decentralized Identifiers (DIDs) and the Verifiable Credentials (VC) Data Model v2.0 [18].

A Decentralized Identifier (DID) is a globally unique identifier that resolves directly to a DID Document containing public cryptographic keys, verification methods, and service endpoints [18]. Crucially, the DID is entirely controlled by the subject rather than a central issuing authority. Verifiable Credentials are tamper-evident, cryptographically signed digital documents (often packaged natively using JSON-LD for maximum semantic interoperability) that definitively prove specific claims about a person, an organization, or an IoT device.

This paradigm operates on an elegant, mathematically secure triangle of trust: an Issuer cryptographically signs a credential, a Holder stores it locally in a digital wallet, and a Verifier seamlessly checks its authenticity [18]. Because the credentials and DIDs are anchored to immutable decentralized ledgers or distributed trust frameworks, verifying the absolute authenticity of the data requires no real-time integration or API callbacks to the issuing authority. This privacy-by-design architecture eliminates centralized honeypots of personal data and vastly accelerates onboarding [18].

Most importantly, in 2026, this trust layer is no longer limited strictly to human identity; it is the fundamental prerequisite for the Agentic Web [2]. If autonomous AI systems are to execute high-stakes financial transactions, access highly structured enterprise data, and operate safely across disparate organizational boundaries, they must possess identifiable, verifiable authority. Systems can utilize Verifiable Credentials to assign cryptographic, granular identity directly to AI agents [18]. Through decentralized governance files containing machine-readable "trust lists," an AI agent can instantly recognize and verify the delegated authority of another agent, establishing a mathematically provable foundation for machine-to-machine collaboration, negotiation, and data exchange without requiring constant human oversight [2].

9. The Agentic Web in Action: Complex Autonomous Scenarios

To truly understand the practical, real-world realization of the 2026 Semantic Web, it is highly useful to revisit the classic use-case scenario of a semantic agent organizing a holiday to London, as originally conceptualized in the early days of the technology [1]. In the early theoretical vision, a human user would type a rigid sentence ("I want to go to London on Holiday from 8 to 15 June"). The agent would process the text, utilize RDF files and ontologies to recognize the concepts of "London" and "Holiday," invoke separate, disconnected web services for flight and hotel bookings, and return a static list of options for the user to manually review [1].

In the fully realized 2026 Agentic Web, this process is vastly more sophisticated, entirely autonomous, and highly conversational. The user no longer types a rigid command; they engage in a continuous, context-aware conversational interface powered by a multimodal LLM. The core intelligence is no longer a single script, but rather an orchestration of specialized sub-tasks managed by multi-agent frameworks.

When the human user requests the London trip, the primary orchestrating agent parses the intent and instantly accesses the user's personal semantic knowledge graph to retrieve deep historical preferences (e.g., a strong preference for boutique hotels over chains, specific dietary restrictions, past travel stressors, and preferred airlines). The orchestrator then spawns dedicated sub-agents: a flight researcher agent, an accommodation agent, and a budget tracker.

These sub-agents interact directly with the open web. However, rather than clumsily scraping airline HTML websites, the flight agent utilizes the new WebMCP protocol to instantly discover and seamlessly invoke the structured booking functions of various airlines, comparing real-time, RDF-compliant pricing and availability schemas.

If a severe disruption occurs—such as a sudden flight cancellation due to weather—the agentic system does not simply fail and return an error code to the user. It utilizes the deep semantic relationships embedded in the travel ontology to dynamically and proactively reroute the itinerary. The agent interacts autonomously with hotel APIs via JSON-LD payloads to adjust check-in dates and secure alternate transport without the user asking.

When the fully optimized itinerary is compiled, the agent presents it to the user. Upon the user simply stating "Book it", the agent utilizes its Verifiable Credential to cryptographically prove to the airline and hotel that it possesses the delegated financial authority to act on the user's behalf [18]. It executes the secure transaction, standardizes the receipt data into RDF triples, and securely updates the user's personal calendar. Throughout this entire autonomous process, robust Agentic AI defenses are deployed: the agent operates within a Trusted Execution Environment (TEE), utilizes capability-based least privilege to ensure it cannot exceed its authorized budget, and logs every consequential decision using human-readable reasoning chains (CoT) to ensure continuous explainability and auditability.

10. Transforming Education: Educational Ontologies and Ambient Learning

The deep integration of Semantic Web technologies has equally revolutionized the domain of education and e-learning. Historically, the Semantic Web was identified as an exceptionally excellent platform for e-learning because learning materials could be interpreted semantically and reorganized dynamically based on user requests. This process relied heavily on semantic queries and navigation through learning materials made possible by ontologies providing exact, machine-readable definitions of complex concepts [1].

By 2026, the traditional, monolithic Learning Management System (LMS)—which merely hosted and deployed static courses—has been largely supplanted by sophisticated "Ambient Learning" architectures. The psychological reality of the "Forgetting Curve"—the phenomenon where humans forget approximately 70% of new information within 24 hours of exposure—is actively mitigated by integrating education directly into the daily workflow. The enterprise strategy has shifted radically from mandatory, periodic "Time-Out Training" to daily, AI-modularized contextual learning, drastically increasing knowledge retention rates to 80% via automated spaced repetition.

This transformation is heavily reliant on the deployment of advanced educational ontologies and semantic metadata. Ontologies standardize the complex vocabulary between learners, human instructors, and automated learning systems, allowing for a coherent organization of knowledge. These domain ontologies model the entire educational

spectrum, including curricula, skill-based requirements, and pedagogical models. When structured data (people, processes, equipment) and unstructured documents are semantically annotated and bridged via enterprise knowledge graphs, they become unified, highly discoverable "knowledge assets".

Intelligent tutoring systems leverage this semantic architecture to generate deeply personalized, adaptive learning paths. By continuously evaluating the learner's current knowledge state against the target ontology, the system dynamically adapts content. It utilizes the relationships defined within the ontology to infer new knowledge pathways, heavily facilitating discovery learning.

Furthermore, Large Language Models integrated directly with these semantic layers automatically standardize legacy educational content. The AI extracts metadata and cleans massive repositories of knowledge assets in minutes—a task that previously required thousands of human hours. This vast acceleration expedites the onboarding of new staff and the development of in-house talent. Because these educational resources are semantically described using W3C standards like RDF and OWL, the resulting data interoperability ensures that highly personalized learning modules can be seamlessly shared, verified, and reused across different digital educational platforms and virtual environments globally.

11. Conclusions

The trajectory of the Semantic Web over the past decade represents a monumental, structural shift from theoretical data interoperability to the functional, secure execution of global autonomous intelligence. The W3C's maturation of the RDF 1.2 and SPARQL 1.2 specifications fundamentally resolved historical inefficiencies in semantic modeling. The introduction of triple terms and advanced annotation syntaxes provided the mathematically sound, scalable data structures desperately required to manage the complex metadata and nested logic demanded by modern AI systems. Concurrently, the modernization of mapping architectures—shifting from rigid, legacy direct-mapping tools to dynamic Virtual Knowledge Graphs and massively scalable materialized graph databases—has successfully bridged the gap between the world's vast relational data silos and the semantic ecosystem.

However, the true realization of the Semantic Web in 2026 is defined entirely by its convergence with Large Language Models and Artificial Intelligence. The severe limitations of probabilistic LLMs have been mitigated by the deterministic truth provided by enterprise knowledge graphs, creating highly reliable, hybrid neuro-symbolic systems. This foundation has given rise to the Agentic Web, rendering obsolete the traditional methods of human-computer interaction and heavily deprecating legacy web services like SOAP. Through innovative protocols like WebMCP and Hydra, the internet has been aggressively retrofitted for machine consumption, allowing AI agents to seamlessly discover, negotiate, and execute complex workflows directly within the browser. Supported by the immutable security of Decentralized Identifiers and Verifiable Credentials, these autonomous systems operate with mathematically verifiable authority and zero-trust

security. Ultimately, the Semantic Web has fulfilled its original, visionary promise: transforming the internet into a cohesive, intelligent environment where machines do not merely display data, but truly understand, reason, and autonomously act upon it to augment human capability.

References

[1] A. ALTĂR-SAMUEL, A. COSTIN, and D. ENACHE, "RDF & RDF Query Languages – building blocks for the semantic web", *Journal of Information Systems & Operations Management,* vol. 9, nr.1, 2015.

[2] Y. YANG et al., "Agentic Web: Weaving the Next Web with AI Agents", *arXiv preprint arXiv:2507.21206*, July 2025.

[3] P. WARREN and P. MULHOLLAND, "Evaluating Reification with Multi-Valued Properties in a Knowledge Graph", in *Proc. Knowledge Graphs and Semantic Web Conference (KGSWC)*, Madrid, Spain, pp. 92-105, 2022.

[4] J. ARENAS-GUERRERO et al., "Declarative generation of RDF-star graphs from heterogeneous data", *Semantic Web*, vol. 16, no. 2, pp. 1-18, 2025.

[5] G. KELLOGG, O. HARTIG, P.-A. CHAMPIN, and A. SEABORNE, "RDF 1.2 Concepts and Abstract Data Model", *W3C Working Draft*, March 2026.

[6] G. KELLOGG and D. TOMASZUK, "RDF 1.2 Turtle: Terse RDF Triple Language", *W3C Working Draft*, January 2026.

[7] P. HASSE, J. BROEKSTRA, A. EBERHART, and R. Volz, "A Comparison of RDF Query Languages", *AIFB Institute*, Univ. of Karlsruhe, Germany, 2007.

[8] J. DE SMET and R. TAELMAN, "Traqula: Providing a Foundation for The Evolving SPARQL Ecosystem Through Modular Query Parsing, Transformation, and Generation", in *Proc. 23rd Extended Semantic Web Conference (ESWC)*, 2026.

[9] J. ARENAS-GUERRERO et al., "Morph-KGC: Scalable knowledge graph materialization with mapping partitions", *Semantic Web*, vol. 15, no. 1, pp. 1-20, 2024.

[10] E. IGLESIAS, M.-E. VIDAL, D. COLLARANA VARGAS, and D. CHAVES-FRAGA, "Empowering the SDM-RDFizer tool for scaling up to complex knowledge graph creation pipelines", *Semantic Web*, vol. 16, no. 2, 2025.

[11] W. LI, S. WANG, S. WU, Z. GU, and Y. TIAN, "Performance benchmark on semantic web repositories for spatially explicit knowledge graph applications", *Computers, Environment and Urban Systems*, vol. 95, 2022.

[12] M. BARONE, A. ROMANO, G. RICCIO, M. POSTIGLIONE, and V. MOSCATO, "Combining evidence and reasoning for biomedical fact-checking", in *Proc. 48th International ACM SIGIR Conference on Research and Development in Information Retrieval*, pp. 1087-1097, 2025.

[13] M. A. FERRAG, A. LAKAS, N. TIHANYI, and M. DEBBAH, "LLM and AI Agents for Autonomous Systems: A Survey of Applications, Datasets, and Security Challenges", *IEEE Open Journal of Intelligent Transport Systems*, vol. 7, pp. 1-20, February 2026.

[14] Y. HUANG and G. ZENG, "RD-P: A Trustworthy Retrieval-Augmented Prompter with Knowledge Graphs for LLMs", in *Proc. 33rd ACM Int. Conf. on Information and Knowledge Management*, New York, NY, pp. 942-952, October 2024.

[15] X. REN, J. TANG, D. YIN, N. CHAWLA, and C. HUANG, "A Survey of Large Language Models for Graphs", in *Proc. 30th ACM SIGKDD Conference on Knowledge Discovery and Data Mining*, Barcelona, Spain, pp. 6616-6626, Aug. 2024.

[16] M. H. DANG, T. H. T. PHAM, P. MOLLI et al., "Llm4schema.org: Generating schema.org markups with large language models", *Semantic Web*, vol. 16, 2025.

[17] J. SARKAR and G. AGNIHOTRAM, "Model Context Protocol: The Central Nervous System for a New Generation of Artificially Intelligent Agents", *Scientific Journal of Computer Science.*, vol. 1, no. 2, pp. 84-93, December 2025.

[18] S. ACHEME and G. N. EDEGBE, "A Decentralized Identity Framework for Secure Federated Learning in Healthcare", *Journal of Cyber Security*, vol. 8, no. 1, pp. 1-31, January 2026.

Bibliography

ACHEME S. and EDEGBE G. N., "A Decentralized Identity Framework for Secure Federated Learning in Healthcare", *Journal of Cyber Security*, vol. 8, no. 1, pp. 1-31, January 2026.

ALTĂR-SAMUEL A., COSTIN A., and ENACHE D., "RDF & RDF Query Languages – building blocks for the semantic web", ", *Journal of Information Systems & Operations Management,* vol. 9, nr.1, 2015.

ARENAS-GUERRERO J. et al., "Declarative generation of RDF-star graphs from heterogeneous data", *Semantic Web*, vol. 16, no. 2, pp. 1-18, 2025.

ARENAS-GUERRERO J. et al., "Morph-KGC: Scalable knowledge graph materialization with mapping partitions", *Semantic Web*, vol. 15, no. 1, pp. 1-20, 2024.

BARONE M., ROMANO A., RICCIO G., POSTIGLIONE M., and MOSCATO V., "Combining evidence and reasoning for biomedical fact-checking", in *Proc. 48th*

International ACM SIGIR Conference on Research and Development in Information Retrieval, pp. 1087-1097, 2025.

DANG M. H., PHAM T. H. T., MOLLI P. et al., "Llm4schema.org: Generating schema.org markups with large language models", *Semantic Web*, vol. 16, 2025.

DE SMET J. and TAELMAN R., "Traqula: Providing a Foundation for The Evolving SPARQL Ecosystem Through Modular Query Parsing, Transformation, and Generation", in *Proc. 23rd Extended Semantic Web Conference (ESWC)*, 2026.

FERRAG M. A., LAKAS A., TIHANYI N., and DEBBAH M., "LLM and AI Agents for Autonomous Systems: A Survey of Applications, Datasets, and Security Challenges", *IEEE Open Journal of Intelligent Transport Systems*, vol. 7, pp. 1-20, February 2026.

HASSE P., BROEKSTRA J., EBERHART A., and VOLZ R., "A Comparison of RDF Query Languages", *AIFB Institute*, Univ. of Karlsruhe, Germany, 2007.

HUANG Y. and ZENG G., "RD-P: A Trustworthy Retrieval-Augmented Prompter with Knowledge Graphs for LLMs", in *Proc. 33rd ACM Int. Conf. on Information and Knowledge Management*, New York, NY, pp. 942-952, October 2024.

IGLESIAS E., VIDAL M.-E., COLLARANA VARGAS D., and CHAVES-FRAGA D., "Empowering the SDM-RDFizer tool for scaling up to complex knowledge graph creation pipelines", *Semantic Web*, vol. 16, no. 2, 2025.

KELLOGG G. and TOMASZUK D., "RDF 1.2 Turtle: Terse RDF Triple Language", *W3C Working Draft*, January 2026.

KELLOGG G., HARTIG O., CHAMPIN P.-A., and SEABORNE A., "RDF 1.2 Concepts and Abstract Data Model", *W3C Working Draft*, March 2026.

LI W., WANG S., WU S., GU Z., and TIAN Y., "Performance benchmark on semantic web repositories for spatially explicit knowledge graph applications", *Computers, Environment and Urban Systems*, vol. 95, 2022.

REN X., TANG J., YIN D., CHAWLA N., and HUANG C., "A Survey of Large Language Models for Graphs", in *Proc. 30th ACM SIGKDD Conference on Knowledge Discovery and Data Mining*, Barcelona, Spain, pp. 6616-6626, Aug. 2024.

SARKAR J. and AGNIHOTRAM G., "Model Context Protocol: The Central Nervous System for a New Generation of Artificially Intelligent Agents", *Scientific Journal of Computer Science*, vol. 1, no. 2, pp. 84-93, December 2025.

WARREN P. and MULHOLLAND P., "Evaluating Reification with Multi-Valued Properties in a Knowledge Graph", in *Proc. Knowledge Graphs and Semantic Web Conference (KGSWC),* Madrid, Spain, pp. 92-105, 2022.

YANG Y. et al., "Agentic Web: Weaving the Next Web with AI Agents", *arXiv preprint arXiv*:2507.21206, July 2025.

https://www.persistencemarketresearch.com/market-research/semantic-knowledge-graphing-market.asp, Semantic Knowledge Graphing Market Size, Share, and Growth Forecast, 2026 - 2033, Date of last access as 24-02-2026.

https://www.marketsandmarkets.com/Market-Reports/semantic-web-market-15328110.html, Semantic Web Market Size, Share, Growth & Forecast 2030 – Markets and Markets, Date of last access as 22-02-2026.

https://dev.to/vaib/the-agentic-web-ai-agents-and-the-power-of-semantic-data-4o2e, The Agentic Web: AI Agents and the Power of Semantic Data - DEV Community, Date of last access as 21-02-2026.

https://www.netcomlearning.com/blog/diving-into-the-era-of-open-agentic-web, The Open Agentic Web: How AI Agents Are Reshaping Work in 2026 - NetCom Learning, Date of last access as 24-02-2026.

https://graphdb.ontotext.com/documentation/11.2/rdf-sparql-star.html, RDF-star and SPARQL-star — GraphDB 11.2 documentation, Date of last access as 20-02-2026.

https://www.ontotext.com/knowledgehub/fundamentals/what-is-rdf-star/, What Is RDF-star | Ontotext Fundamentals, Date of last access as 24-02-2026.

https://www.w3.org/groups/wg/rdf-star/publications, RDF & SPARQL Working Group - Publications - W3C, Date of last access as 18-02-2026.

https://w3c.github.io/rdf-new/spec/, What's New in RDF 1.2, Date of last access as 18-02-2026.

CHANGES IN LEGAL PROFESSION BROUGHT BY AI AND THEIR INTEGRATION IN SERBIAN PRACTICE

Uros ATANASKOVIC[1]
Alexandros KAPOULAS[2]
Ivana NIKOLIC[3]
Srdjan NIKOLIC[4]

Abstract

This study investigates the application of artificial intelligence (AI) in the legal industry through the transformation of the legal profession in South East Europe (SEE) the case of the Republic of Serbia. The study was conducted on the data, collected through literature review and semi-structured interviews with Serbian lawyers. The data shows that Western law firms used AI extensively, while Serbian lawyers are still at a basic level. This gap is due to a delay in AI tool availability in Eastern Europe. The existing literature on the transformation process offers various potential forms of change, though it remains uncertain whether these will be significant or not. There is no consensus on the overall impact of such transformation. Instead, authors present three different perspectives: pessimistic, optimistic, and moderate. The decision that lawyers must make regarding the adoption of AI is not predetermined. They must individually choose the approaches and tools that best support their practice. In Serbia, many lawyers remain unaware of AI's transformative potential, but this is expected to change as AI adoption increases on local level. This investigation codifies various applications and potential transformations within the legal profession in one place. The lawyers should be better informed to embrace changes and adopt existing best practices in AI. The interviewees identified three principal topics while using AI around which they expect future issues, disputes and legal matters to arise ethical implications and liability, personal data protection and privacy issues and intellectual property.

Keywords: Artificial intelligence, legal profession, transformation, Serbia, Serbian practice

JEL Classification: L84.

[1] Lawyer, Law Firm Atanasković I Božović, Partner, Belgrade, Serbia, uros.atanaskovic@atanaskovic-bozovic.com
[2] Associate Professor, Research Director, School of Business, University of York Europe Campus, akapoulas@yorkeuropecampus.eu.
[3] Assistant professor, School of Business, University of York Europe Campus, inikolic@yorkeuropecampus.eu.
[4] Assistant professor, Faculty of Business Studies, Megatrend University, Belgrade, Serbia, srdjan.nikolic431@gmail.com.

1. Introduction

"*The legal profession has remained largely unaffected by new technology for several decades and was overdue for a shake-up.*"

(Hodgson, L. Generative AI Lead at Linklaters)

Many issues have emerged with the latest advances and in digitalization and artificial intelligence ("AI") In fact, AI represents most uncertain technology of our time, provoking feelings of considerable fear and insecurity. On one hand, the business owners and employers are certainly doing their best to exploit and benefit from any new possibility to increase productivity and reduce costs, and on the other, the employees fear from cut-backs and wonder how will these developments affect their jobs and income [18]. For the time being, it seems that AI will become both (i) a new tool, facilitating the execution of work and sometimes even enabling performance of new tasks, and (ii) a reason for termination of some work posts [23].

Effects of digitalization will however vary in different industries [26], and according to some opinions, the legal profession is among the few that are exposed the most [23]. As always with novelties, opinions are divided. One excessively pessimistic, saying that AI will be the end of legal profession and cause massive unemployment, and the other, moderate, upholding the view that AI will assume only some of the functions but never fully replace a well trained professional [10]. There are also few excessive optimists arguing that the disruption caused by AI will actually result in job creation [58].

This paper aims to address these issues from perspective of law firms in Serbia. It explores whatever and how AI can assist (or is already assisting) legal professionals in performing their work more efficiently and productively, and points out the modalities of artificial intelligence applications in which it makes sense to invest. To be more specific, the research was guided by the following questions:

(a) In what ways, in general, is AI affecting and/or changing the legal profession, and, specifically, what are the most notable changes and transformations in legal profession brought by the AI?

(b) How law firms and attorneys are responding and how receptive they are in respect to these changes in western markets and in Serbia (e.g. how Serbian law firms and attorneys respond to these changes, are they missing on any opportunities and do they keep up the pace with their peers from bigger markets?

The objectives of the research were:

- To explore to what extent the AI is being applied in legal profession and in what ways and how such application of AI or emergence of AI is changing the legal profession;
- To assess how receptive law firms and attorneys are in respect to all these transformations, both in general and specifically in Serbia; and
- attempt offering some guidance to attorneys and law firms that could help them implement AI into their legal practice.

2. Literature Review

Theoretical Background

"*It's important that lawyers are familiar with AI technology in the same way they are with the internet now. Those that don't use it will face a bit of an existential risk.*"

(Kewley, J., Partner and Co-Chair of the Global Tech Group at Clifford Chance)

It is highlighted that the concept of AI and digitalization is not new in legal practice. On the contrary, the law firms have been flirting with these technical developments and their potential for some time now, as in case – for example – of automated drafting of contracts, billing systems, Skype, Teams, etc. [38]. However, the introduction of ChatGPT has most certainly accelerated these processes and caused a mild panic among law firms [59].

Generally speaking, macroeconomic and technological environment unmistakably points in the direction of digital technology, and legal profession must realize and accept AI reality and adapt to it in an early stage or the lawyers may end up holding a second-tier status and significance [17]. This adaptation does not only mean that the law firms shall simply use new digital tools and technologies in the process in order to replicate existing services in a digital form; it also implies changing business processes, identity, corporate practice and culture and skill sets of attorneys [43]. In contrast to these arguments, other authors suggest that there is a hype present in relation to this topic, as so many law firms initiated processes of AI implementation without much thinking or analyzing effects, some by developing their own AI tools and some by licensing them from big IT companies, such as "Harvey" or "Cocounsel" ([48]; [44]; [19]). According to [8], one should be prudent when adopting and applying digitalization and AI on existing practice, as most AI projects fail – as high as 80% of new projects [8]. However, to be fair, not all law firms share the same enthusiasm. According to some authors [41], in some firms attorneys are using AI covertly, without knowledge or approval of their management. Overall, the current literature shows that certain changes and limitations are already underway.

2.1 Specific applications of AI in legal practice

Legal profession has been a subject of digitalization for a time now. However, AI seems to be causing a real disruption in the profession. The literature highlights several ways in which AI is utilized by law firms so far:

- *Financial and management software* – usually are used for billing or project management, have been around for a time now [39]. Besides that, we need to take in consideration that a number of law firms still limits IT tools and AI capacities [31].
- *Legal research* - Legal research, as an AI function is novelty brought by ChatGPT, as it possesses extremely robust research capabilities. The greatest applicability potential is in legal research and writing ([19]; [59]; [54]). Some studies though pose the question as to how accurate and trustworthy its output really is, as ChatGPT still tends to manufacture data itself; the phenomenon called "AI hallucination" ([24]; [58]). There is an already well known case of New York lawyer who admitted to have used ChatGPT when preparing his legal argument and it turned out that AI cited several court cases that did not exist [25]. Furthermore, in some cases the lawyers have already been sanctioned for submitting fake quotes and citations, because of AI use [27]. As – at the end of the day – the lawyers will stand responsible for everything that goes out of their office.
- *E-discovery* – this is one of the specific variations that deserves to be mentioned. Namely, one of quite useful functions of AI is cutting through enormous volumes of electronic data and identifying relevant documents and – usually problematic – information [56].
- *Document review, analysis and drafting contracts/briefs* – this function is similar to legal research, aimed to analyze large volumes of legal documents and identify key information (e.g. case law or specific clauses). This function is widely accepted by many lawyers and discussed by many authors as one of repetitive tasks that will be performed in future by AI ([19]; [58]; [1] ; [39]; [66]; [4]). To reiterate, many lawyers see the greatest potential of AI precisely in legal research and writing [54]. It would seem that ChatGPT has already been used to draft contracts. Naturally, the version it produces cannot be used *as is*, an experienced attorney must vet it. Nevertheless, AI proved to be a solid solution for preparing initial drafts, especially of less complex and demanding contracts or memorandums in a matter of minutes ([2]; [39]; [66]; [9]). As for the briefs, the lawyers should be more than cautious there. As already mentioned, the "AI hallucinations" when citing case law still represent serious and frequent issue ([21]; [24]; [58]). Some research pinpoint cases where lawyers were sued for underperformance due to the non-critical use of AI [64]. Anyhow, it will be expected that AI of the future will become just another tool available to everyone, something like a spell-check tool or a calculator ([54]; [45]). The lawyers must make sure they are competent in using these technologies, understand how to use them and be aware of their limitations and potential biases.

Researchers explore a number of legal industry specific AI products, such as (i) *Lexis+ AI,* developed by *Lexis Nexis* and supported by some large US law firms (Baker McKenzie, Reed Smith LLP and Foley & Lardner LLP), (ii) *Harvey*, built on OpenAI and ChatGPT technology, or (iii) *Bloomberg Law* ([21]; [1]). All these products include all or almost all the functions discussed above, and they are still under further development. However, to be clear, the applicability of these products and AI is still limited. As [16] correctly points out, there is a "technological frontier", still growing but nevertheless existing, within which – on one hand – AI can complement or replace human work, and outside which – on the other hand – AI output is inaccurate and degrades human work.

In any case, in terms of application, is looks like AI will take over repetitive and standardized tasks, while competent lawyers will provide final touch i.e. review and editing, and – even though AI will not fully replace lawyers – the ones who do not adapt fast enough may be overran by their more adaptable competitors.

The functionality and efficiency of these applications is certainly one of the topics to be further followed up and analyzed, by both academics and practitioners. But it must also be noted that, for the time being, these applications seem to emerge and exist only on the richest markets of the world. Actually, the vast majority of AI products mentioned originates from the US or the British market, meaning it is based on and deals with the common (Anglo-Saxon) and not continental (Roman-based) law. On these markets, the largest law firms develop their own AI solutions, while vendors offer licensing arrangements to small and midsized firms [51]. At the same time, the pressure to use AI and keep up with competitors, one way or another, is rising [13]. Smaller markets, such as SEE and Serbia, shall have their turn only after the larger ones are saturated enough. In addition, this is a gap that needs to be filled not only in terms of products and practice but also accompanying academic works.

There is also the ethical aspect that is unclear. On one hand, there are court and public authorities not too inclined to accept the use of these new technologies in practice [27]. On the other, however, there are positions saying that (need the page where you got this from?) but the lawyers must stay ultimately responsible and liable for the product that comes out of their office ([57]; [19]; [14]; [44]; [56]). This is a very important point to be followed-up and further investigated, both in terms of regulation of AI application and in terms of its entry and acceptance in practice.

2.2 Transformation of legal profession

General observations and the rise of legal portals

Arrival of AI caused certain transformations in the legal profession itself, whereas some of them already have a clear outcome, and some of them are still unclear as they are in initial stages. The attitude of legal industry shows several faces: the moderate one, the pessimistic

one, and the optimistic one.

The *moderate opinion* is that AI brings enhancements to personal productivity of attorneys, but does not seem to bring any transformational change to comprehensive workflows. In other words, AI did not change the industry, it just made the lawyers faster by replacing some of the grunt work performed by juniors and enhancing the overall performance of experienced lawyers who still have to supervise the process and the outcome ([20]; [50]; [63]).

The *pessimistic position* argues that the rapidly developing AI technology poses significant risk to individuals and society ([29]; [30]; [40]; [12]). According to this perspective, even a plain simplification of work and time savings could disrupt the industry and put the junior lawyers' work at risk [4], as AI could potentially replace them. Even in case the junior lawyers are not replaced but instead only need to evolve and become experts in *AI prompt engineering*, a great deal of people would be affected as many of them would not have necessary skills to keep up with the changes [49].

According to the *optimists*, such as [57], AI will not lead to job losses; it will result in job creation. Further, [15] argues that historically "worker displacement from innovation is typically offset by new job creation". He further argues that this is not the first time the technology is creating more efficiency in legal work and that it was happening for decades (emails, electronic documents and submissions, online conference call, etc.), and that "if history informs the future, the long-term economic impact of innovation will be growth". They admit nevertheless that upskilling in AI related competencies will be necessary and that practitioners who understand how to use it well will have an advantage.

Whatever the answer to the previous discussion, the future is expected to somehow blend AI and human "functionalities". There is a very interesting view offered by [16] regarding different modalities or approaches of use of these new applications. According to this article, there are "two distinctive patterns of successful AI use by humans along a spectrum of human-AI integration". One is called "Centaurs" – where consultants (or lawyers) act as "half-horse/half-humans" by dividing and delegating their solution-creation activities to the AI or to themselves, and the other "Cyborgs" – where people integrate their task flow with the AI and continually interact with technology without any clear boundary in delegated activities. It may be presumed that some kind of *best practice* will emerge from all these different approaches, whereas such *best practice* would be an interesting topic for further research by again both practitioners and academics.

Delivery of legal services through digital platforms existed for a time now on large markets, such as Chinese or European [38]. These online services went from: (i) just putting a potential client in touch with the lawyer with appropriate expertise to (ii) providing software with automatic design of legal documents, such as contracts. However, lately these portals seem to have been entering the lawyers' domain in a more serious way that might

even endanger and drastically change the future of the legal profession. The recent literature discusses a number of these portals, such as *FreeLawChat.ai*, *Law* ChatGPT *and LegalZoom,* whereas the authors express mainly affirmative positions on the subject ([51]; [28]; [32]; [54]).

Reportedly, the portals do not offer legal advice and do not replace lawyers, but rather "provide user-tailored information on basic issues" (e.g. "on the waiting period for divorce, the advantages and disadvantages of limited liability companies" and the like). However, "when it comes to determining the best course of action for an individual in a complex situation, the legal advice of a licensed attorney is essential" [52].

For the time being, the profession is trying to protect itself and some of these portals, such as *LegalZoom* and *Parsons Technology,* have been used on multiple occasions for violating unauthorized practice of law rules [33]. The most often argument aiming to justify their existence is help to poor and underprivileged people, who cannot afford to hire a real lawyer. This way, allegedly, the justice is made more accessible to them (Goth, 2024; [32]; [54]) Anyhow, it looks like the portals are here to stay.

Legal Tech Lawyers

The literature further implies that the AI gave birth to another important and fundamental change, a completely new breed of lawyers – "legal tech lawyers" – with different identity and culture, and playing a completely different game ([37]; [47]; [46]; [43]; [3]). These lawyers wear t-shirts instead of suits and use more colloquial language, they occupy open-spaces (similar to small IT firms) instead of expensive offices or have no space at all [38], and – obviously – they use technology. Finally yet importantly, they see themselves as business-people, not lawyers, newcomers in the profession. It appears to be quite difficult for an experienced traditional lawyer to jump ship; there are even articles testifying to internal conflicts and "identity splits" experienced by traditional lawyers trying to deliver an "online gig" [65]. So consequently, this sector will grow as more and more young lawyers chose to become this kind of animal.

However, even though it is a characteristic of "legal tech firms" to incorporate both law and technology and employ not only lawyers but also IT and AI experts, engineers, and analysts [7], it must be noted that recently traditional law firm started to act in the same way. All these changes in the job landscape even lead to a changed law school curricula at the University of Liverpool, now including modules on legal tech tools [3].

Changes in profession paradigm, internal environment and pricing

"AI removes the excuse of hour's spent, so private practice lawyers will have to change the way they measure their contribution."

(Winfield, M. Global Director of Commercial, Legal and Digital Risks at Buro Happold)

According to [38], in the near future legal profession will require lower level of knowledge intensity and professionalization of workforce, as technology will allow certain simplifications, as well as higher level of capital intensity and dependence, due to necessary investments in technology. More importantly, according to some authors, soon, legal services will have to be provided in a much cheaper and more convenient way ([60]; [31]). And this to such extent that the very paradigms of legal profession will be changed, for example (i) "one to one" service will become "one-to-many" service, (ii) print base will become – and is already becoming – IT based legal systems, (iii) reactive service will become proactive service, etc.

According to literature, internal organization, structure and processes in law firms are changing as well, in more than one way. More and more – law firms introduce non-lawyer CEOs to run the company, and allow possibility of external ownership over company shares [38]. What is also interesting is that the time necessary for a junior lawyer to become partner is getting shorter and shorter, as technology is eliminating loads of repetitive work that juniors were usually performing during their first years on the job [3]. Some authors argue that these new technologies will upgrade the life balance in legal profession, by reducing the amount of hours associates need to bill in order to meet their quotas and at the same time get a comparable revenue. Apparently, the burnout rate in legal profession is higher than in any other industry [4].

The pressure on hourly rates is not a new thing in legal industry [6]. The literature shows that well before the serious digitalization and AI development, the client has hated hourly rates and demanded predictability in legal costs [61]. According to [5], by applying hourly rates the lawyers expect the clients to suspend the rules of basic economics, consumer and price psychology, to turn their eye blind and "hand-over a blank check". Nowadays, this pressure increases, as clients expect law firms to integrate AI tools and thus increase efficiency and reduce costs, along with billable hours and invoices ([59]; [39]; [56]). Further, new approaches to provision of legal services caused by digitalization and AI resulted in new billing models, such as value-based pricing, differentiated pricing, volume discounts, etc. ([36]; [37]; [59]).

2.3 New legal matters and receptiveness

Digitalization projects and AI use for various purposes and in various industries, such as self-driving cars, application of AI in medicine, and global e-trading solutions, open various legal issues [38] that primarily concern security, personal data protection, confidentiality, and intellectual property ([39]; [48]). These issues stem from the feed to and use by the AI of sensitive (personal or confidential) information of – for example – consumers, clients or employees ([45]; [42]) and the problems with maintaining the privacy and confidentiality of such information once fed to AI.

Another area of law that is already affected by application of AI are intellectual property ("IP") rights. One interesting example discussed in the literature is the issue of whether AI-assisted inventions or author's work should be protected as IP rights. For example, in some jurisdictions, US, for the time being, the competent authorities require that in case AI was used in the process of creation of invention or a work of art, a human being must provide "significant contribution" in the process; whereas – for example – constructing a prompt "in view of a specific problem to elicit a particular solution from the AI system" should be acknowledged as such significant contribution. On the other hand, Indian Government took a different stand, that there will be no specific rules regarding the AI generated work and that an "author" of such computer-generated work is the person who causes the work to be created, without any specific requirements whatsoever (such as "significant contribution"). Consequently, we can very easily imagine a situation where an AI generated patent, or a copyright is allowed to be registered in India but denied in the US.

Finally, 2024 seems to be the year of birth of many AI regulations throughout the world. The most important one in Europe is certainly the *Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024* (the "AI Act") [67], the first-ever legal framework on AI that addresses the risks of AI, on one hand forbidding certain applications of AI and on the other limiting and strictly regulating some others. The emergence of AI Act, as well as the other similar regulations, shall for sure generate considerable amount of new work for the lawyers.

Considering everything above, it should be mentioned that – even though the legal industry is falling behind the general consulting profession in identifying and establishing digitalization and AI as specialization niche [43] – it is becoming uncontestably clear that law firms will and already are creating highly specialized AI lawyers and departments [48].

In general, the literature says that the legal industry has always been slower than others in accepting technological disruptors ([4]; [9]; [17]; [36]; [11]). According to [58], there is a pattern in law firms' reactions to technological advancements: they usually start with skepticism and resistance, pass on to denial and finish by reluctant adoption. Something like the Kübler-Ross' *five stages of death*.

However, even though this process is usually very slow ([53]; [19]; [43]), it looks like ChatGPT changed everything, in the sense that everybody picked up speed and want to participate in the new game ([62]; [9]; [4]; [13]; [28]). According to [4], "for the first time, the legal industry is in the lead in adopting new technology, and that's creating disruption like never before". Numerous (law) firms are already employing AI in many ways ([19]; [24]; [36]; [37]; [56]), sometimes even giving it too much credit and confidence [25]. What is interesting is that both big law and small law firms are equally eager to implement AI, although they meet different impediments on that road: (i) big law firms have their large legacy infrastructure that is difficult to move, while (ii) smaller firms meet investment requirements often exceeding their financial capabilities [39].

However, they are also aware that they must be cautious especially after the affair in New York with the made-up cases [34]. So AI is mostly used as a tool, whereas the results it generates are (or should be) closely monitored. In other words, AI is still not a replacement for the sound judgment of an attorney as it can generate incorrect content [45]. However – nevertheless – it looks like everybody will have to use it – one way of another. There are traces of acceptance of AI by judges; a judge in Texas started instructing the acting lawyers to disclose whether they are using AI in their briefs and arguments [28]. Further, many law schools grapple with its use on exams and essays, whereas some of them permit AI use while the others prohibit it [58]. Therefore, it will be interesting to follow up on how new coming lawyers and students will conduct research and be trained in the years to come.

In most cases, current literature treats these topics separately from each other; for instance, only the application modalities. In addition, different changes in profession are discussed in different articles. On the contrary, this paper represents an attempt to encompass and, in a way, "codify" various aspects of change in one place and possibly point out their interconnection. It explores simultaneously the changes in day-to-day work and practice caused (or yet to be caused) by AI, the changes in the nature and organization of legal profession and law firms, along with changes in service-charging-modalities and increasing number of new legal matters brought by AI applications. Finally yet importantly, the paper introduces perspective of continental and smaller markets, as opposed to Anglo-Saxon and English-speaking markets, and alludes to the slower development and smaller level of AI application on the former compared to the latter.

3. Methodology

3.1 Secondary data collection

Given that AI has entered the legal profession some time ago, some experiences have settled already, and there is a number of examples of its use in both the practice and academic articles. Secondary data, collected from the latest literature treating these matters, the AI applications are many. The legal profession is undergoing certain transformation(s) already, there is a number of new legal topics and matters stemming directly or indirectly from AI's existence and application, while the level of acceptance of AI application among lawyers is quite high.

3.2 Primary data collection

Researchers employed semi-structured expert interviews. The interviews were carried out with attorneys working in small and mid-size law firms from Serbia, finding themselves at the very beginnings of AI application. Around one third of the interviewees are at the level of partners in their respective firms, while the rest of them are senior associates and mid-

level associates. Data were collected through individual interviews in English, in written form, and participants' identities remained anonymous.

3.3 Respondents

There were fifteen interviewees in total, of different ages, positions and experience (in the table below). Majority of them (eleven) practice various areas of business law, while four of them specialize in litigation.

No.	Sex	Age	Position	Experience	Education	Area of Law
R1	*Male*	*47*	*Partner*[5]	*18*	*LLM*	*Business Law*
R2	*Male*	*46*	*Partner*	*18*	*LLB*	*Litigation*
R3	*Male*	*45*	*Partner*	*17*	*LLM*	*Business Law*
R4	*Male*	*46*	*Partner*	*17*	*LLB*	*Litigation*
R5	*Male*	*44*	*Partner*	*16*	*LLM*	*Business Law*
R6	*Male*	*41*	*Senior Associate*	*15*	*LLB*	*Business Law*
R7	*Male*	*36*	*Senior Associate*	*12*	*LLB*	*Business Law*
R8	*Male*	*34*	*Senior Associate*	*11*	*LLM*	*Business Law*
R9	*Female*	*34*	*Senior Associate*	*10*	*LLB*	*Business Law*
R10	*Female*	*31*	*Senior Associate*	*8*	*LLB*	*Business Law*
R11	*Female*	*32*	*Senior Associate*	*8*	*LLM*	*Business Law*
R12	*Female*	*31*	*Senior Associate*	*7*	*LLB*	*Business Law*
R13	*Female*	*32*	*Junior Associate*	*6*	*LLB*	*Business Law*
R14	*Male*	*28*	*Junior Associate*	*4*	*LLB*	*Litigation*
R15	*Male*	*28*	*Junior Associate*	*4*	*LLB*	*Litigation*

Table 1: List of participants

*created by authors

Themes emerged from thematic analysis of interviews mostly coincide with the themes identified in the literature review. Such a tie between literature review and interview results

[5] [1]"Partner" is an attorney who owns interest in the law firm and receives a share of the profits. In other words, he or she is a co-owner of the business at hand (in this case – legal practice), in a same way a shareholder is a co-owner of a company.

is not accidental, naturally, but rather stems from the questions that served as basis for interviews, which more or less follow the themes and subjects identified in literature review.

3.4 Limitations

In terms of limitations of this research, its principal flaws stem from the shortfalls of interviews as research method. The most important one is that interviews cannot be free of bias. According to [22], p162, "people are inherently biased, both the interviewer in formulating and interpreting, and interviewees in providing answers". On the other hand, the interviewee cannot avoid incorporating his/her biases into answers, or – even worse – will not be 100% honest, bearing in mind that the interviews cannot really be fully anonymous. Finally, the interpretation of data is perhaps the most tricky and sensitive part. [36] point out the data analysis as one of the most sensitive moments of qualitative research and call attention to the risk of accusations of manipulating and interpreting data in a way that supports the interviewer's personal agenda.

Another limitation worth mentioning is that this research is of rather limited reach. As the primary data will be collected from only fifteen attorneys practicing only on the Serbian market, the conclusions and recommendations stemming from this paper cannot be generalized. On the other hand, they could probably be of some help to small and mid-sized law firms practicing on South-East European markets. It will in any case provide a better picture of AI application on legal markets that are less developed than the US and the Western European. The researchers leave the extent to which this investigation's findings apply to other situations in this sector in SEE and beyond to the readers in those situations that is referred to as reader or use generalizability highlighted by Merriam 1998 as cited in [35]. Even more, it will provide a rather clear picture of how these less developed markets will look like soon, as the secondary data stemming from the literature in its vast part describes the situation and circumstances existing "at the West" that are yet to come "to the East".

4. Results and discussion

4.1 General perspective and receptiveness

When asked about the general situation in economy in terms of AI applications, some 20% of interviewees were not familiar, 30% were somewhat familiar, and 50% were quite familiar with current events and circumstances. Lawyers from the latter group were even able to elaborate, to offer a few examples from practice and specify industries that are most affected by change.

Most of interviewees stated IT and technology sector, marketing, healthcare and finance as

the sectors which are affected the most. But they also mention trade (retail and e-commerce), banking, gaming, logistics and transportation, HR, legal industry, and creative occupations (such as web design, copyrighting, industrial design, graphic design, etc.).

Significance, acceptance and effects of AI in legal industry of Serbia

As for legal industry, all interviewees agree that AI brings change. One half believes that the AI is bringing important if not revolutionary changes that will increase efficiency by automating routine tasks and save their time left and right in performance of their daily duties, such as document review, translations, legal research, and document analysis. The other half of interviewees demonstrated certain level of skepticism regarding the reach of AI, for various reasons. What is interesting, the skeptical ones seemed more up to speed with the topic and offered some sound arguments for their position, as follows:

- One of the interviewees doubted that legal industry will be affected as much as the others, and pointed out that AI can be used only on certain terrain e.g. in certain aspects of legal services:.. *"I see them more linked to the advisory sector of the legal industry, rather than being fully applicable to traditional services such as litigation, which often involve in person hearings".*
- Another insisted on importance of human aspect in provision of legal services:*"…the legal profession remains inherently people-centric, requiring not only technical knowledge but also understanding human psychology and social norms"*.
- Finally, few interviewees observed that the AI application will have much more to offer in jurisdictions and legal systems built on common law (as opposed to continental / Roman law): *"…especially for countries whose legal systems are based on precedent law, as it includes a lot of researching and looking at the previous judicial cases".*

However, the interviewees apparently saw and discussed AI as a tool only, aimed at increasing the efficiency of their work. They did not recognize and acknowledge the transformation potential of AI. They concentrated mostly on application modalities of AI and loss of work, seemingly unaware of deeper processes and transformations elaborated in literature. However, the lawyers from both groups acknowledged both positive and negative effects of AI in the future.

On the one hand, one-fifth of the respondents do not seem very interested in adopting new practices, let alone specializing in AI-related issues. Such a position was expressed by several senior lawyers, mostly partners. They would "*prefer that younger colleagues take over this part of business knowledge"* or – at best – to *"know the basic rules and be familiar to the extent that they can give advice".*

The rest of interviewees are open to adopting new practices and knowledge and show high awareness that "AI increasingly changes the legal industry", and that "there is a growing

need for professionals who understand both law and technology". Even though their position is prevalently positive, there are two general impressions that emerge out from these interviews:(i) there does not appear to be any hype yet in relation to this topic, as described by some authors in reference to the Western markets, and (ii) there is likely to be resistance towards full outsourcing and entrusting work to AI, as rightfully noticed by [55].

All interviewees except one see the AI as useful tool, they only do not agree on significance i.e. level of such usefulness. Even though a few of them raised the issues regarding the privacy, confidentiality and accuracy concerns, they mostly believe that AI will make their work easier, not replace them; at least not instantly (on the short run). However, they do believe that in near future AI will bring certain troubles, especially for younger generations as *"the work that was so far reserved for trainees and junior lawyers will be more and more completed by AI tools"*.

When asked about a longer-term AI perspective, however, the negative opinions multiplied. One half of them still believed that the negative effect of AI will be limited and that AI will perform only certain repetitive day-to-day tasks, such as document review and legal research, *"while lawyers will focus on more complex tasks that require human judgment"*. Overall, this group does not see considerable reduction in the number of lawyers in the coming years.

Another group, a bit smaller than one-half of respondents, fearing that negative effects will be of greater significance. These respondents believe that, in time, positions such as trainees, assistants, paralegals and junior lawyers will be reduced while *"the future will be bright for partners of law firms*". Thus, mostly younger attorneys expressed fear. One interviewee that showed a distinctly negative attitude argued that *"considering human influence and their potential abuse, creating unfair competition in the market as well as giving advantage to rich and large law offices that will be able to apply the mentioned tools first"….. "AI will cause huge changes in the market, going so far as to replace the work of people"*.

The two darkest views shared by respondents predict a negative outcome for the legal profession, and state the following:

- *"At the end, I believe that the attorneys will be a dying profession. Revolution will happen, and the AI will be able to provide better legal analysis, draft a better agreement, perform more thorough research, etc. than any human being ever could. This will all mean that the world will perhaps still need attorneys, but twenty times less attorneys than it needs right now."*
- *"The future of the legal profession in light of the aforementioned changes does not seem too optimistic to me. It will definitely lead to certain adaptations, but time will tell whether these adaptations will be enough to continue make a living from the practice of law as a primary means of earning."*

This darker perspective can also find support in literature, among the pessimists, saying for example that AI will be the end of legal profession and cause massive unemployment [10]. Finally, it should be noted that there were no excessively optimistic interviewees, believing that AI may result in job creation, as argued by [57] or [15].

4.2 Specific applications of AI in Serbia

Most of the interviewed lawyers, roughly 80%, confirmed that they used the AI (e.g. Chat GPT) one-way or another for: legal research, drafting of legal documents and other functions.

As for specific functions, most of interviewees (around 80%), mentioned initial legal research as a most notable function of AI. Out of these 80%, one third emphasized that the Anglo-Saxon legal systems will be much more affected e.g. that the AI contribution there will be much more significant, due to the use of precedents. On the other hand, the interviewees demonstrated awareness that AI outputs still tend to be inaccurate and thus demonstrated a high level of vigilance. When asked to what extent they personally use it for these purposes, some 60% (out of all interviewees) confirmed that they do – but more as a guideline than a source. Thus, it may be concluded that relying on AI is still much less important among Serbian lawyers than it is in the western hemisphere.

Around half of interviewees stated drafting of legal documents as important contribution and confirmed that they used it for this purpose. Furthermore, most respondents stated that, in terms of the type of document, they use AI for creating simple agreements, and not at all for creating briefs to be submitted to courts and other public authorities. Hence, the interviewees' positions coincide only partially to the literature review. On one hand, the literature also sees AI as a good solution for preparing initial drafts of less complex and demanding contracts or memorandums ([1]; [39]; [66]; [9]), which goes hand in hand with the interviewees' answers. On the other hand, the respondents do not use it for litigation related purposes, as do the western lawyers (according to the literature).

One fourth of interviewees (mostly partners), in one way or the other, considered organization and management as the field in which AI will be of help. In any case, the number is not impressive. Apparently, not many lawyers and law firms in Serbia use AI for these purposes. Perhaps only the few big ones. This is probably due to a small market and the absence of real corporatization of law firms. Only one or two interviewees mentioned document analysis, E-discovery, and predictive outcome analysis as functions they thought of. When presented with these options, the respondents mostly agree that AI "could be useful" in that way too. However, legal software and applications on the Serbian market are still in the initial development stage. Therefore, features like these will have to wait a bit more before they enter the practice. This is also the reason for discrepancy between the literature and the interview results.

In principle, the respondents still use the AI on a basic level, the results they get are still not quite impressive, and that is very well reflected in the answer one of them has given: *"The ChatGPT products were very useful in terms of time-saving, but not complete and ready for distribution to clients. It did require my additional work on any and all documents before having them ready for the clients."*.

As for the specialized AI tools for lawyers, around half of interviewees expressed awareness that specialized AI solutions are already used to a great extent at the USA, England and some countries of EU, while small countries still work with Chat GPT. Only one attorney mentioned a local law firm using a certain specialized AI solution, but only because it belongs to a network concentrated around a big Anglo-Saxon law firm (and the specialized AI solution at hand is built on basis of Anglo-Saxon legal system) It should be noted that, the incorporation of AI features into existing legal software solutions and applications on the Serbian market underway.

4.3 Transformation of legal profession in Serbia

One fourth of interviewees has no formed opinion regarding the changes that will transform the legal profession in one way or another; they do not seem neither impressed nor particularly worried. Nor aware, for that matter. More than half of interviewees see the changes only in terms of increased efficiency and productivity of individual attorneys, which may have positive and/or negative effects. They do not show awareness regarding the possibility that the profession itself may be transformed at its very roots. This corresponds to the moderate viewpoint presented in the literature review, pleading that AI brings enhancement in productivity but does not recognize transformational changes of the profession.

Only two respondents demonstrated some understanding of a possible transformed future, and they were both pessimistic. However, their perspective was mostly concentrated on changes in terms of negative effects of AI in the future and gravitated more toward operational change, rather than appearance of true transformational effects within the profession. Their perspective was captured in the two following quotes:

- *"Traditional methods still dominate, and AI tools are generally viewed as supplementary. However, there is a growing awareness of the potential for AI to reshape the legal landscape, particularly in areas like document review, legal research, and client interactions."*
- *"The nature of work will be significantly changed because certain jobs will be automated, the number of people (lawyers and especially interns) will be reduced, and the impact on prices will be that certain services will be canceled and/or will not be charged for, which will be compensated by increasing the price of services that will not be performed using AI tools."*

As it may be seen, the Serbian lawyers are still mostly unaware of possibility that the profession may be substantially changed (theoretically) in the coming years. Further, specifically, none of the interviewees was aware of appointment of non-lawyer CEOs, nor external ownership of shares in Serbian law firms, as opposed to the trends depicted in the literature [36]. Actually, as they explained, external ownership of shares in law firms would not even be possible under Serbian laws. There were however some opinions on legal portals, "legal tech lawyers", and changes in pricing methodologies.

The interviewees were not aware of any real portal for the provision of legal services on the Serbian market. Few of them referred to certain internet sites existing on the local market that provide templates of legal documents that may be downloaded by the visitors. However, in reality, this "online service" is far even from even the simplest services and functions described in the literature.

Legal portals as discussed in literature are still not present in Serbia. Hence, the overall picture is not very impressive and the AI application in legal profession is still scarce. However, it must be noted that lawyers are still in the situation to use only Chat GPT and not a specialized programs and applications, such as "Harvey", "Lexis+ AI" or "CoCounsel". It may therefore be argued that there is no lack of interest and that the level of application may only rise once the specialized applications arrive to the market.

Several interviewees showed the interest in becoming a "legal tech lawyer". But nobody from the interviewed attorneys is taking any steps in that direction yet. Moreover, none of them actually had in mind the meaning of that term as described in the literature – a whole new breed of lawyers with different identity and culture, and playing a completely different game compared to traditional lawyers ([37]; [47]; [46]; [43]; [3]). The respondents meant more on specialists in AI matters. Only after a short explanation, they fully understood the idea, but they also mostly agreed that it might be a bit late to change approach in such a profound way.

Only few interviewees demonstrated a vague interest in becoming „legal tech lawyers". And all of them were young, which matches the claim from the literature that *"usually, these "legal tech lawyers" seem to be newcomers in the profession. And it appears to be quite difficult for an experienced traditional lawyer to jump ship. So consequently, this sector will grow as more and more young lawyers choose to become this kind of animal"*.

The interviewees identified three principal topic around which they expect future issues, disputes and legal matters to arise:

- Ethical implications and liability stemming from misuse or mistakes made while using AI;
- Personal data protection and privacy issues, and
- intellectual property related cases that will arise from situations in which AI fully or partially generated some kind of creative work that might (or not) be protected

by copyright or similar intellectual property rights.

As for the legal matters, the interview results to a large degree match the literature. They both singled out the same concerns: (i) security, (ii) personal data protection, (iii) confidentiality, and (iv) intellectual property. The only discrepancies between the two are the lack of awareness among Serbian lawyers that AI may cause discrimination if used in HR proceedings and low expectancy of any relevant quantity of work to be generated by new AI legislation.

6. Conclusion

The first comprehensive law to legally regulate artificial intelligence - the EU Artificial Intelligence Law (*Regulation (EU) 2024/1689*) [67], was adopted in 2024, with its phased implementation commencing in 2025. The legal framework governing artificial intelligence in Serbia is currently undergoing transformation. In 2019, Serbia became the first country in SEE to adopt the National Strategy for the Development of Artificial Intelligence for the period 2020-2025 (*"Official Herald of the Republic of Serbia", No. 96/2019*) This initiative positioned Serbia as one of 11 countries globally to include AI at a state level, according to the UNESCO report (2021). In 2021, it founded the first Artificial Intelligence Institute, and in 2022, it became part of the Global Partnership for Artificial Intelligence (GPAI, 2024). Finally, on January 10, 2025, the Government of the Republic of Serbia adopted the Strategy for the Development of Artificial Intelligence for the period 2025-2030, based on Article 13. Law on the Planning System of the Republic of Serbia (Official Gazette of the Republic of Serbia, no. 30/18).

There is no doubt that there will be many more applications of AI in legal industry in the years to come. Academia must follow up what are the new emerging ways of employment of AI in legal industry, as well as to what extent are the existing models further developed and perfection, and how will this affect the profession.

According to interview results, Serbian lawyers are still much closer to basic rather than advanced level of using AI. This primarily due to delay in development and arrival of specialized AI tools on Eastern European markets. Once these tools arrive to Serbia, they will already be tuned and used in accordance with best practices, so consequently the Serbian legal practice hopefully won't have to go through the same mistakes the western practices did.

Along the same lines, the claim that the legal industry (in general) is in lead in adopting AI in its practice, does not really stand in Serbia. Given that the specialized AI tools are not even on the market yet, at this point the legal profession's position in Serbia may only be anticipated (with some level of probability) Bearing in mind that most interviewees demonstrated a moderately positive opinion regarding the AI application, an guess would be that the AI tools will be well accepted once they enter application. Even though some of

the respondents showed a certain level of fear – especially the younger ones, due to the possibility that, they might be replaced – it is also the younger ones who are open to accepting new knowledge and practices. Hence, the change will probably be carried out by young lawyers and new generations.

Finally, it should be noted that, the incorporation of AI features into existing legal software solutions and applications on the Serbian market underway.

Regarding the transformation process, the current literature only offers an insight into several possible forms (or ways) of transformation that could turn out to be important.

There are authors advocating three different points of view: pessimistic, optimistic and moderate. Namely, the choice to be made by lawyers regarding the adoption and application of AI is not preordained [33]. It appears that all make individual choices regarding various approaches and products developed to support their practice. As for the Serbian lawyers, we have seen that they are mostly unaware of transformative potential of the AI. In addition, this is something that will probably change as the use of AI starts to grow on the local market.

Overall, it is very important to continue monitoring this change and the relationship between the two approaches to lawyering (traditional and modern), in order to anticipate further developments and the final outcome. This is most certainly the topic deserving further attention from academia. At the same time, practitioners must stay vigilant in respect to this topic in order to survive.

Further, the functionality and efficiency of AI applications is certainly one of the topics to be further followed up and analyzed, by both academics and practitioners. This paper reflect only the situation at the time of its creation, while the number and variety of innovative practices and business models will certainly continue to grow and without doubt deserve further attention. Smaller markets, such as Balkans and Serbia, shall have their turn only after the larger ones are saturated enough. Consequently, the smaller markets could win the most from this as well as from any following academic work dealing with this subject, as they would be able to learn from experiences analyzed in such works that took place on larger markets.

Acknowledgment

The authors would like to thank all the participants who participated in the research for this study.

References

[1] Anghel, I. - *PwC Introduces AI Chatbot for 4,000 Lawyers to Speed Up Work*. Bloomberg.Com, N.PAG 2023.

[2] Anghel, I. - *Consulting Giants See AI Shaving Years Off the Path to Partner*. Bloomberg.Com, N.PAG 2023.

[3] Anghel, I. - *Law Firms Are Recruiting More AI Experts as Clients Demand "More for Less."* Bloomberg.Com, N.PAG 2023.

[4] Bagley, J. - *When Ai Goes to Court. Utah Business.* Aspen Law & Business 2024.

[5] Baker, R. - *The Professional's Guide to Value Pricing,* Aspen, Aspen Law & Business 2003.

[6] Baker, R. - *The Firm of the Future: A Guide for Accountants, Lawyers, and Other Professional Services*. Oxford, John Wiley & Sons. 2003.

[7] Bannerman, N. - *Greenberg Traurig welcomes Joshua Forman to technology practice in Miami*. Capacity Magazine, N.PAG 2023.

[8] Bojinov, I. - *Keep Your AI Projects on Track*. Harvard Business Review 2023

[9] Brady, N. M. - *"A post-Covid lawyer's take on the practice of law."* Indiana Lawyer, volume 35 no. 7. pp.8. 2024

[10] Brochner, N. M. - *Will AI Replace Lawyers?* www.forbes.com. 2023

[11] Callegari, B., & Rai, R. S. - *"Digitalization and law: innovating around the boundaries."* Journal of Professions & Organization, volume 9 no. 3, pp. 291–302. 2022.

[12] Cicek, M., Gursoy, D. & Lu, L. - *Adverse impacts of revealing the presence of "Artificial Intelligence (AI)" technology in product and service descriptions on purchase intentions: the mediating role of emotional trust and the moderating role of perceived risk.* Journal of Hospitality Marketing & Management 2024.

[13] Correia, J. - *"Safety Hazard: Four Things Lawyers Should Consider Before Using Artificial Intelligence."* Indiana Lawyer. volume 35 no. 3, pp.12. 2024

[14] Correia, J. - *Is AI for U? Lawyer Should Keep an Eye on Artificial Intelligence*. Indybar. 2023

[15] Crutchfield, K. - *AI Won't Replace Lawyers - But It Will Change How They Work.* Above the law. 2024

[16] Dell'Acqua, F., McFowland III, E., Mollick, M., Lifshitz-Assaf, H., Kellogg, C. K., Rajendran, S., Krayer, L., Candelon, F. and Lakhani, R. K. - *Navigating the Jagged Technological Frontier: Field Experimental Evidence of the Effects of AI on Knowledge Worker Productivity and Quality.* Harvard Business School. 2024

[17] Destefano, M., Tellmann, B. P., & Wu, D. - *"Don't Let the Digital Tail Wag the Transformation Dog: A Digital Transformation Roadmap for Corporate Counsel."* Journal of Business & Technology Law. volumr 17 no. 2. pp.183–262. 2022.

[18] Diaconu, B. - *The economic vision of artificial intelligence's (AI) efficiency.* Theoretical and Applied Economics, volume 3 no.636. 2023

[19] Dickerson, C. R. - *"A review of leading AI programs in the legal industry."* Indiana Lawyer, volume. 34 no. 16. pp.5–18. 2023

[20] Dolan, B. - *"Ready to Litigate: Next Generation of Lawyers Find Region Perfect Place to Start Careers."* Northwest Indiana Business Magazine. pp. 20–24. 2024

[21] Dolmetsch, C. - *Legal Data Firm Makes Push to Introduce AI to Lawyers' Work*. Bloomberg.Com, N.PAG. 2023

[22] Driscoll, D.T. - *Introduction to Primary Research: Observations, Surveys, and Interviews.* Writing Spaces: Reading on Writing, pp.153-174. 2011

[23] Felten, E., Raj, M. & Seamans, R. - *How will Language Modelers like ChatGPT Affect Occupations and Industries?* NYU Stern School of Business. 2023

[24] Fenwick, T. - *"An inevitable reality."* Indiana Lawyer, volume 34 no. 15. pp. 7–9. 2024

[25] Frayne, A. - *"New laws coming to curtail artificial intelligence (AI)"* Governance Directions, volume 75 no.6. pp. 987–989. 2023

[26] Goldfarb, A., Taska, B., & Teodoridis, F. - *"Artificial Intelligence in Healthcare? Evidence from Online Job Postings."* AEA Papers and Proceedings, volume 110 no. 5. 2020

[27] Gopal, L. - *"Lawyers Sanctioned for Failure to Correct Faulty Reliance on Fake Cases, Quotations, and Citations Invented by ChatGPT."* Business Law Today, pp. 49–52. 2024

[28] Goth, G. - *"Why Are Lawyers Afraid of AI? Generative artificial intelligence and the law: there is no turning back."* Communications of the ACM, volume 67 no. 1. pp. 14–16. 2024

[29] Guha, A., Grewal, D., Kopalle, P. K., Haenlein, M., Schneider, M. J., Jung, H., Moustafa, R., Hegde, D. R., & Hawkins, G. - *"How artificial intelligence will affect the future of retailing."* Journal of Retailing, volume 97 no. 1. pp. 28–41. 2021

[30] Haan, K. - *Over 75% of consumers are concerned about misinformation from artificial Intelligence*. Forbes, 2023

[31] Holanda Maia, S. M., & Coutinho de Melo, F. J. - *"Maturity 4.0 in the Law Service: A Systematic Review of the Literature."* Revista Gestão Em Análise, volume 12 no. 3., pp. 7–29. 2023.

[32] Holmes, H. - *"Making the Justice Leap."* AALL Spectrum, volume 28 no. 6. pp. 10–13. (2024)

[33] Hughes, H. - *"Robots, Markets, and the Value of Deal Lawyers."* Journal of Corporation Law, volume 49 no. 4. pp. 833–871. (2024)

[34] Jones, M. - *"Raising the Bar."* Utah Business, volume 39 no. 6. pp. 4. (2024)

[35] Kapoulas, A**.,** Murphy, W., Ellis, N. - *Say Hello, Wave Goodbye: Missed Opportunities for Electronic Relationship Marketing within the Financial Services Sector?* International Journal of Bank Marketing, volume 20 no. 7. pp.302-310. 2002

[36] Kapoulas A. & Mitic M. - *"Understanding challenges of qualitative research: rhetorical issues and reality traps."* Qualitative Market Research: An International Journal, volume 15 no. 4. pp. 354 – 368. 2012

[36] Kronblad, C. - *"Digital innovation in law firms: The dominant logic under threat." Creativity & Innovation Management*, volume 29 no. 3. 2020

[37] Kronblad, C. & Jensen, S. H. - *"Being a professional is not the same as acting professionally'—How digital technologies have empowered the creation and enactment of a new professional identity in law."* Journal of Professions & Organization, volume 10 no. 2. 2023

[38] Kronblad, C. - *How Digitalization Changes our Understanding of Professional Service Firms*. Academy of Management Discoveries, volume 6 no. 3. pp.436–454. (2020)

[39] Lai, K. - *"Human plus machine": future of AI and law firms*. International Financial Law Review, N.PAG. (2023)

[40] Longoni, C., Bonezzi, A., & Morewedge, C. K. - *"Resistance to medical artificial intelligence."* Journal of Consumer Research, volume 46 no. 4, pp. 629–650. 2019

[41] Marcotte, S. - *AI will help HR Teams boost their Productivity and Efficiency.* Workforce Solutions Review, 2023

[42] Marshall, R. C., Plowman, J. N. W., Linnabary, M. P. F., & Ogunro, A. A. - "Artificial Intelligence and Employment Law." *Employee Relations Law Journal*, volume 50 no. 1. pp. 27–33. 2024

[43] McKenna, P. J. - *"Digital Transformation Practice"*. Of Counsel, volume 38 no.11. 13–15. 2019

[44] Mehta, R. - *"From HR to PR: how one firm is developing its own AI."* Managing Intellectual Property, N.PAG. (2023)

[45] Miller, K. W. & Martinez, A. - *"Adopting AI: The efficiencies and risks for lawyers."* Indiana Lawyer, volume 35 no. 13. pp. 8–9. 2024

[46] Noordegraaf, M. - *"Protective or Connective Professionalism? How Connected Professionals Can (Still) Act as Autonomous and Authoritative Experts."* Journal of Professions and Organization, pp. 7. 2020

[47] Noordegraaf, M., and Brock, D. - *"Protective and Connective Professionalism: What We Have Learned and What We Still Would Like to Learn."* Journal of Professions and Organization, volume 8 no. 2. 2021

[48] O'Neill, R. - *"AI queries 'explode', but which law firms can capitalize?."* Managing Intellectual Property, N.PAG, 2023

[49] Oarue-Itseuwa, E. - *"Artificial Intelligence's Impact of the Management Consultancy Sector over the Next Five Years."* Management Consulting Journal, 2024

[50] Raisinghani, V. - *"Will Your M&A Lawyer Be Replaced By AI? Attorneys are grappling with the potential consequences of AI-powered legal tools that could transform their industry."* Mergers & Acquisitions, 2024

[51] Redmond, K. - *"Better call Bot: How AI technology can allow attorneys to work more effectively and efficiently."* Njbiz, volume 37 no. 3. pp. 9–10. 2024

[52] Redmond, K. - *"AI ipsa loquitur: Basking Ridge-based Lawyer.com rolls out artificial intelligence to provide basic information on the law and practitioners."* Njbiz*,* 2024

[53] Redmond, K. - *"New chat: As the use of AI grows in the legal profession, firms wrestle with questions about the technology."* Njbiz, volume 36 no. 37. pp. 2–7. 2023

[54] Robert, A. - *"Bridging the Gap."* ABA Journal, volume 110 no. 1. pp. 39. (2024)

[55] Samokhvalov, K. - *"The Transformative Impact of Artificial Intelligence on the Management Consultancy Sector."* Management Consulting Journal, 2024

[56] Sholli, S. - *"AI is changing the way law firms work here's how."* Managing Intellectual Property, N.PAG., 2023

[57] Smith, R. A., & Weber, L. - *"How AI Is Changing the Roles of Doctors, Lawyers and Marketers."* Wall Street Journal - Online Edition, N.PAG. (2024)

[58] Smith, M. L. - *"AI and the Legal Landscape: Do not fear a zombie apocalypse."* ABA Journal, volume 110 no. 1. pp. 6. (2024)

[59] Smith, L., & Stark, K. - *"The Potential Impact of Generative AI on Law Firms."* Of Counsel, volume 42 no. 8. pp. 6–8. (2023)

[60] Susskind, R. - *Tomorrow lawyers.* New York: Oxford University Press, 2023

[61] Taylor, S. T. - *"Firms Continue to Hire Specialists to Help Get the Price Right."* Of Counsel, volume 34 no. 2. 2015

[62] Tchernookova, A. - *Law firms advise clients to press on with AI compliance.*

International Financial Law Review, N.PAG. 2023

[63] Udovita P. - *Conceptual Review on Dimensions of Digital Transformation in Modern Era. International Journal of Scientific and Research Publications*. Department of Marketing Management, University of Kelaniya, 2020

[64] Voreacos, D. - *Jho Low-Linked Rapper Appeals Conviction, Citing Lawyer's AI Use*. Bloomberg.Com, N.PAG. 2023

[65] Yao, Y. - *"One foot in the online gig economy: Coping with a splitting professional identity."* Journal of Professions & Organization, volume 9 no. 3. pp.273–290. https://doi.org/10.1093/jpo/joac015 2022

[66] Yoders, J. - *"Construction Attorneys Get an AI Assist in Document Crunch."* ENR: Engineering News-Record, volume 292 no. 5. 2024

[67] Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonized rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Artificial Intelligence Act) (Text with EEA relevance)

Bibliography

Atkinson, K., Bench-Capon, T. & Bollegala, D. - *Explanation in AI and law: Past, present and future.* Elsevier B.V., Artificial Intelligence, Volume 289, December 2020, 103387. https://doi.org/10.1016/j.artint.2020.103387 , December 2020

Ashley, K.D. - *"A Brief History of the Changing Roles of Case Prediction in AI and Law."* Law in Context, volume 36 no.1. pp. 93-112. DOI: https://doi.org/10.26826/law-in-context.v36i1.88, September 2019

Richmond, K.M., Muddamsetty, S.M., Gammeltoft-Hansen, T. et al. - *Explainable AI and Law: An Evidential Survey*. DISO 3, 1, https://doi.org/10.1007/s44206-023-00081-z, December 2023

Surden, H. - *Artificial Intelligence and Law: An Overview*, 35 Ga. St. U. L. Rev. 2019

Surden, H. - *Ethics of AI in Law: Basic Questions*. The Oxford Handbook of Ethics of AI, chapter 38, https://doi.org/10.1093/oxfordhb/9780190067397.013.46, July 2020

Surden, H. - *ChatGPT, Artificial Intelligence (AI) Large Language Models, and Law* Fordham Law Review, volume 92, U of Colorado Law Legal Studies Research Paper no. 24-15, Available at SSRN: https://ssrn.com/abstract=4779694, March 2024

THE IMPACT OF DIGITALIZATION AND AUTOMATION ON THE ACCOUNTING PROFFESION IN ROMANIA: A QUALITATIVE STUDY

Lucian – Cosmin BĂDĂLĂU[1]
Georgiana - Janina SOARE[2]

Abstract:

This research endeavor aims to identify the level of digitalization within the largest accounting and consulting firms in the Romanian market, the impact of digitalization and automation on these entities, and the obstacles encountered throughout the digitalization and process automation transition. The purpose is to highlight the probability of future job losses, as well as the opportunities emerging from the digitalization of the accounting profession. Furthermore, the research seeks to elucidate the opinions of professionals regarding this context and the requirements of employers concerning the skills that young graduates in the field must possess. Methodologically, a qualitative approach was employed, consisting of semi-structured interviews applied to 10 accounting professionals (directors, partners, and senior managers) operating within the largest accounting and consulting service providers in Romania. The results were interpreted based on Actor-Network Theory (ANT) to examine how networks are developed and maintained, as well as the interaction roles played by various actors in the transformation of the accounting profession following its digitalization. The research corroborates the findings of previous studies regarding firm competitiveness and their investments in technology (Jylhä și Syynimaa, 2019). Additionally, the study's findings are consistent with the results of other research asserting that accountants' tasks will be transformed, while human involvement will remain necessary for specific activities (Kokina și Blanchette, 2019; Holmes și Douglass, 2021). [1]; [2].

Keywords: automation, accounting profession, digitalization, impact, competitiveness, semi-structured interview, Actor-Network Theory (ANT).

JEL Classification: M41 – Accounting

1. Introduction

Drawing on Actor-Network Theory (ANT), this research endeavor focuses on the transformation process generated by automation within the financial-accounting field and the role played by actors in this process. Consequently, the research aims to identify the

[1] Universitatea "Valahia"din Târgoviște, România, lucian.badalau@gmail.com
[2] PhD assistant, University Spiru Haret, Faculty of Economic Sciences Câmpulung Address: 223 Traian Street,115100 Câmpulung, Argeș, România, Corresponding author: georgiana.soare@spiruharet.ro

impact of automation on the accounting profession within the largest outsourced accounting service firms in Romania, alongside other significant aspects related to this subject. To achieve its objective, the study utilizes a qualitative approach based on semi-structured interviews as its primary method. In this regard, the main goal is to address the following research question: *How has automation transformed the accounting profession in Romania?*

In Romania, the accounting profession is heavily legislated by state institutions, similar to France; however, regarding accounting regulation, it interfaces with other economic disciplines such as statistics, taxation, micro and macroeconomics, and legal sciences, resembling liberal states like the United Kingdom or the United States (Cobzaru, 2018). The primary accounting normative acts in Romania are Legea contabilității nr. 82/1991, O.M.F.P. nr. 1802/2014—which presents a single set of accounting rules for both individual and consolidated financial statements—O.M.F.P. nr. 2861/2009 regarding the inventory of assets and liabilities, O.M.F.P. nr. 2634/2015 concerning accounting documents, Legea nr. 227/2015 regarding the Tax Code, the Tax Procedure Code, and Legea nr. 31/1990 regarding companies. Romanian accounting standards comply with the rules provided in the Fourth and Seventh European Directives adopted through O.M.F.P. nr. 1802/2014 and those stipulated in IFRS for certain companies and groups of companies. The professional organization regulating the accounting profession in Romania is the Body of Expert and Licensed Accountants of Romania (CECCAR). It is empowered to maintain registers for its members, establish initial and continuing professional development requirements, and set ethical standards. The organization comprises expert accountants and licensed accountants, and for public practice, membership is mandatory (IFAC, 2021). CECCAR is taking the necessary steps to adapt to new expectations regarding the skill sets and roles of accountants for the upcoming changes (Popa și Șova, 2020). Although Romania ranks last in the European standings regarding the Digital Economy and Society Index (DESI), tax authorities appear to be making efforts to digitalize the accounting and tax system and to perform company audits automatically. Within this context, starting in 2022, certain companies were required to report all accounting information through the Standard Audit File for Tax (SAF-T) system. The primary role of SAF-T was to standardize the transfer of information between tax authorities and taxpayers, providing benefits to both parties. SAF-T involves the periodic reporting of a set of information (initially and additionally, in a predefined format) that facilitates the review by tax authorities of the operations carried out by taxpayers (PwC, 2021). This new standard aims to reduce the VAT collection gap and digitalize tax inspections (Deloitte, 2021). Another requirement from the tax authorities for certain taxpayers, starting in 2022, was related to the electronic invoice (RO e-factura). According to EY (2022), the creation of this system, as well as the use of the electronic invoice, contributed to achieving public policy priorities such as the digitalization of public sector activity, financial transparency, and the promotion of sustainable development. Simultaneously, the electronic invoice and the use of the SAF-T system will specifically reduce costs and increase the efficiency of the public sector.

2. Literature Review

The evolution of technologies such as cloud computing, blockchain, artificial intelligence, big data, RPA, digital reporting, and other related tools has had and continues to have a significant impact on how accounting is conducted in contemporary practice. Regarding this subject, previous studies have focused on how various technologies are utilized or implemented in the accounting field (Dilla și Raschke, 2015; Kokina și Blanchette, 2016; Ma et al., 2021) [3];[1];[4], what the advantages and disadvantages of using new technologies in accounting are (Bogasiu și Ardeleanu, 2021), or what the accountants' perception is regarding this aspect (Macovei et al., 2021) [5]. However, the literature regarding the impact of digitalization, and especially automation, on the accounting profession remains limited. The term "automation" encompasses a broad range of technologies aimed at reducing human intervention within processes. The automation of the accounting profession is not a new subject, but attention to this topic has increased significantly in recent years. In the 20th century, when accounting began its transition to computers, many researchers directed their attention to the automation of accounting, discussing its impact on the field and on accountants (Keenoy, 1958; Kerremans et al., 1991; Wilson și Sangster, 1992) [6];[7];[8]. Currently, attention is directed toward new automation tools and how they influence the accounting profession, as well as the transformations regarding the jobs of accounting practitioners. In this regard, researchers have discussed various automation tools, such as artificial intelligence (AI), robotic process automation (RPA), or optical character recognition (OCR), utilized by accountants in automating processes to facilitate their work and ensure greater accuracy. AI tools represent systems programmed to function and think like human intelligence, but possessing the capability to perform tasks better than humans. This capability is attributed to the experimental aspect of computer science involved in programming an intelligent machine capable of functioning across various tasks using its own intelligence (Dongre et al., 2020) [9]. On the other hand, RPA represents the automation of structured, rule-based activities and repetitive operations typically performed by humans (Cohen et al., 2019) [10]. OCR represents business solutions used to convert handwritten or typed texts into machine-readable formats (Gotthardt et al., 2020). Used in conjunction, these three tools can represent an ideal for automating accountants' work, thereby limiting human intervention and improving business processes (Shidaganti et al., 2021). Although these technologies are widely utilized at the level of accounting firms and internal accounting departments, human intervention is still required for other activities such as data processing and analysis. Regarding this topic, Kokina și Blanchette (2019) [1], in their paper concerning RPA in accounting, conclude that accounting practitioners will have other opportunities, such as exception analysis, robotic software development, support, and testing, even if employees are likely to be replaced by robots for certain tasks. Additionally, skills related to data management, data cleansing, and the correction of incomplete and inaccurate data will remain within the purview of employees rather than computers (Holmes și Douglass, 2021) [2]. Furthermore, the results of the study conducted by Mohammad et al. (2020) maintain that humans are still necessary for data analysis and interpretation, as well as for creativity and imagination, while their former jobs will be taken over by codes and AI-based robots. As demonstrated by the findings of the aforementioned studies, the accounting profession

will not disappear in the future, but accountants' jobs will undergo transformations, and the primary skills they should possess are IT-related. Automation exerts an influence not only on accountants' jobs but also on accounting firms. In this regard, Jylhä și Syynimaa (2019) found that the use of new technologies will increase productivity and price competition. Moreover, the authors assert that accounting firms unwilling to invest in or utilize technology are at risk of disappearing from the market. Other aspects relate to data quality and consistency, which will be improved through automation, alongside faster reporting speeds, enhanced process focus, an extended range of services, reduced costs, and expanded IT qualifications for employees (KPMG, 2017). While the aforementioned studies have identified the impact of automation on the accounting profession across different contexts, the present research aims to identify the influence of digitalization and automation on accounting within the Romanian context.

3. Research methodology

To achieve the objective of identifying the impact of digitalization and automation on the accounting profession, a qualitative method based on semi-structured interviews was selected. In researching the transformation of the accounting profession within the Romanian context, previous studies have employed the interview as a qualitative method (Albu et al., 2021; Albu et al., 2011) [11];[12], alongside other qualitative approaches (Feleagă, L., și Feleagă, N., 2016). This method facilitates an understanding of how various actors contribute to this transformation, the identification of the level of automation within accounting firms, and the influence that automation exerts on the accounting industry. In total, 10 interviews were conducted with directors, partners, senior managers, and automation managers involved in the digitalization and automation of accounting, operating within the 10 largest accounting firms in Romania. This context was selected considering the level of the DESI index recorded by Romania, even in 2023. In this regard, the aim was to ascertain whether this ranking is valid in Romania, alongside determining the level of digitalization and automation within the accounting profession. Furthermore, according to the study conducted by Lowe (2004) [13], a local investigation is necessary to uncover the nature of accounting practice. The interviews were conducted between May 2023 and February 2024, lasting approximately one hour each, with the exception of the initial interview. Table 1 presents the list of interviewees, the duration of each session, and the precise date on which each interview was conducted.

Table 1. List of interviews.

Ref. No.	Position within the company	Abbreviation	Duration (min)	Date
I1	Partner	Non Big 4.1	120	05.05.2023
I2	Partner	Non Big 4.2	60	14.11.2023
I3	Senior Manager	Big 4.1	60	24.11.2023

I4	Senior Manager	Big 4.2	60	06.12.2023
I5	Senior Manager	Non Big 4.3	60	07.12.2023
I6	Director	Non Big 4.4	60	28.12.2023
I7	Senior Manager	Non Big 4.5	60	29.01.2024
I8	Director/ Automation Manager	Big 4.3	60	02.02.2024
I9	Automation Manager	Non Big 4.6	60	08.02.2024
I10	Partner	Big 4.4	60	10.02.2024

Source: Author's elaboration adapted from Albu et al. (2011) [12].

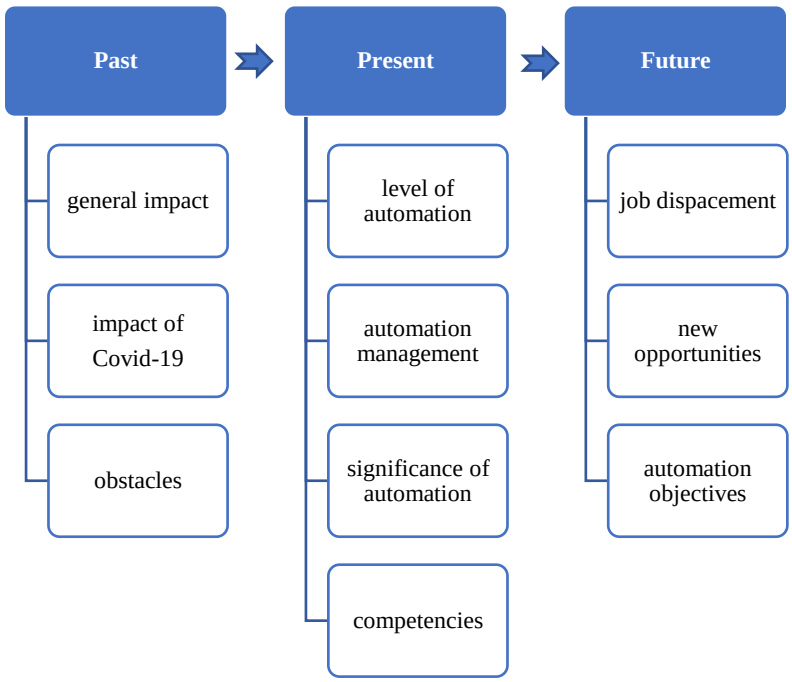
The interviews were conducted face-to-face or via online meeting platforms (Zoom, Google Meets, Teams). They were carried out in Romanian and subsequently translated into English. During each interview, notes were taken and transcribed immediately upon completion to prevent the loss of details. The interviews were analyzed using the directed content analysis technique (Hsieh și Shannon, 2005) [14]. For conducting qualitative research, the utilization of theory was necessary to provide comprehensive and complex understandings of the subject matter. To better explain the transformation process of the accounting field due to automation and the impact that automation exerts on the profession, the study relied on Actor-Network Theory (ANT). This social theory was proposed by Callon M. (1986), Law J. (2007), and Latour B. (2005), and was initially utilized in the fields of technology and science. Employing this theory, researchers can better investigate how accounting intervenes in local actions and the interconnections among accountants, the technology they use, and inscriptions (O'Connell et al., 2014) [15]. ANT specifically examines how networks are developed and maintained, as well as the interaction roles of various actors within the transformation (O'Connell et al., 2014) [15]. Essentially, ANT is an analytical framework that generates new knowledge resulting from identifying the roles humans and non-humans play in structuring networks among technology, people, and their ideas (Latour, 2005; Callon, 1986; Law, 2007). This theory pays significant attention to the transformation process and analyzes how innovation is gradually constructed or translated through a network of diverse actors (Latour, 2005). In the case of the present research, interest was directed toward the role of actors in the accounting automation process and how they contribute to this transformation, aiming to identify the impact on the profession. According to the study conducted by Latour (2005), an actor is represented by an individual or non-individual entity that affects another entity, giving meaning to a certain phenomenon that influences that entity. Every element of the network must cooperate and play its role to help the network remain stable, considering that actors depend on one another, regardless of their nature (human or non-human) (Law, 2007). Within the conducted research, the implementation and utilization of automation tools in accounting processes—which in turn

influence the accounting profession—are driven by networks of human and non-human actors, such as accounting employees, managers, tax authorities, clients, automation solution providers, technological tools, and the Covid-19 pandemic. ANT has been widely utilized in accounting research. For instance, Albu et al. (2020) [16] employed this approach to explain the transformation process generated by the implementation of costing tools in Romanian construction companies, while Murro și Beuren (2016) [17] utilized this theory to interpret the findings related to the investigation of the specialized accounting inspection process. Additionally, Alsharari N.M. (2016) [18] applied ANT to explain the diffusion of management accounting innovation in the public sector as a result of the influence of International Monetary Fund reforms.

4. Research findings

To offer a clearer perspective on the impact of automation on the accounting profession, the data are presented in chronological order, commencing with the existing impact of automation on the profession, the manner in which the Covid-19 pandemic contributed to this impact, and the principal obstacles encountered by outsourced accounting service firms during the automation processes. The second stage encompasses the level of automation, its management within the firms, its significance for accounting professionals, and the newly required competencies. The final stage pertains to the future of automation within the accounting industry, specifically focusing on the objectives of the firms, the new working models, and the emerging opportunities. These stages are illustrated in Figure 1, with each phase exerting consequences on the subsequent one(s).

Figure 1. Chronological stages of automating the accounting profession.



Source: Authors' elaboration.

4.1 The impact of automation and obstacles encountered

"Automation is not a topic of yesterday or today; it is as old as the world. Nowadays, because technology has become so cheap and accessible to everyone, everybody is thinking about how to automate." (I2 - Non-Big 4.2).

But how can the impact of automation on the accounting profession be quantified? More precisely, how can one discern whether the impact is positive or negative? For accounting firms, the impact might be positive, while for certain employees for whom change management represents a massive challenge, it could be negative. Overall, the interviewees consider that automation has positively affected the accounting profession at the level of companies providing accounting services, yet it simultaneously carries certain negative aspects. In this regard, one of the interviewees explained: "It has had a positive and far-reaching impact because automation, on the one hand, has simplified the work and theoretically reduces the risk of human error, but it affected us (the company) because everything is changing, and everyone is implementing automation. […] We spent many months finding an Optical Character Recognition (OCR) provider that we could afford. OCR costs are high. Over time, the cost is recovered, but you need the initial investment. You pay now, but the results come over time. […] Automation reduces human resource costs but adds costs associated with the systems utilized. Efficiency is seen not only in money but also in the time spent. The reduction in time leads to cost reduction and faster delivery of results to clients." (I1 - Non-Big 4.1).

As the aforementioned interviewee suggested, the positive impact of automation also involved costs at the company level. Although human resource costs decrease, costs related to automation tools increase, and the benefits materialize over time. From the paragraph above, it can be understood that the actors driving the change brought about by automation are accounting systems and market competitors. If a company on the market implements automation tools, ideally the others should implement them as well to keep pace, as the probability of losing clients is quite high. This finding is consistent with the results of the study conducted by Jylhä and Syynimaa (2019), which shows that accounting firms unwilling to invest in or utilize technology are at risk of disappearing. Regarding this issue, another interviewee expressed their opinion: "In 3 years, practices such as paperwork or organizations that have not adopted the new matter (automation) will disappear from the market because clients will no longer pay them. For the younger generation, the ideal cannot be shuffling papers. New generations no longer accept these things. And you, as an organization, will no longer have either people or clients." (I2 - Non-Big 4.2). Another actor, as mentioned above, is the young accountant belonging to the millennial generation (White et al., 2020), and what defines this generation is their affinity with the digital world (PwC, 2020). As the above interviewee suggested, the new generation no longer accepts working with paper, and this would lead to even more automated accounting. However, some of the interviewees consider that the impact of automation has not been so significant and that there is still room for automation in the accounting industry. "It affected it (the accounting profession) less than I would have liked, in the sense that, my vision remains that there is a

huge potential in utilizing automation in accounting and in processes generally. The benefits are significant, and the costs are low." (I2 - Non-Big 4.2). "I believe we are in the first stage of this transformation; there is no maturity in the market yet." (I8 – Big 4.3).

This first stage of transformation, as highlighted above, was amplified by the Covid-19 pandemic for certain companies, as accountants' work shifted from the office to remote work. In Romania, prior to the Covid-19 pandemic, clients used to bring the folder with printed documents to the accounting firm, and the accountant used that folder to record transactions in the accounting system. Today, this practice no longer exists, at least for large accounting firms. Regarding this topic, one of the study participants explained: "It (the Covid-19 pandemic) accelerated it drastically (automation). When we worked from the office, some clients sent documents physically, while others electronically. We couldn't believe that effectively starting from the second day of lockdown we worked remotely. […] If the pandemic hadn't occurred, it would have taken much longer to convince the clients." (I8 – Big 4.3). The fact that the pandemic influenced the automation of accounting was approved by seven out of the ten interviewees. The Covid-19 pandemic and the measures imposed by the authorities drastically altered everyone's behavior in this industry. For this reason, the pandemic could be considered another actor that played a significant role in the automation of accounting for certain companies. However, some of the interviewees consider that the Covid-19 pandemic did not bring any change to the level of automation of the accounting profession because, in the companies they work for, things were already initiated prior to this period. "The Covid-19 pandemic increased clients' acceptance of the process, shifting to faster solutions. However, things were initiated beforehand. The Covid-19 pandemic facilitated client acceptance, giving us access to their platforms without them having to send documents via email anymore." (I10 – Big 4.4). "I couldn't say that (the Covid-19 pandemic) contributed to automation, but it helped flexibilize the way we work. Clients started scanning documents, but I wouldn't say automation was an impulse in this direction as a result of the Covid-19 pandemic." (I6 – Non-Big 4.4). The idea of client acceptance was supported by half of the respondents, as they consider that, before the Covid-19 pandemic, clients were very hard to convince to send documents electronically. This would lead us to understand that an obstacle in the automation process is considered to be the client, alongside job security, organizational resistance to change, the price of automation, uncertainty, and many others. As in any other project, in the accounting field too there are various obstacles in the automation process, but only by overcoming these obstacles can companies achieve success.

A portion of the interviewees consider that employees and their resistance to change represent the main obstacle in the automation process. Regarding this issue, one of the interviewees explained: "The main obstacle is the human, the organization's culture, which I do not think is a specific culture. […] There are people for whom doing something else tomorrow is terrible. Resistance to change comes from the fact that we are human. Machines change easily, humans more difficultly. The problem comes from showing people that by accepting it (automation), they will step into a better world. If you do not show them these things, you have no chance. In reality, there is a fear that they become irrelevant. This

type of attitude delays the automation process, but it does not change it. The change happens, but at a lower speed." (I2 – Non-Big 4.2). While the client was somehow forced to change the old way of working in the context of the Covid-19 pandemic, for certain employees it is still difficult to do so. Companies should have a strong change management procedure to make people understand the benefits of automation, because otherwise, a lot of work is required from companies to convince their employees. Regarding this aspect, one of the interviewees mentioned: "People represent the main obstacle (for automation), because the pressure and the workload are high enough that people want to work with the tools and systems they already know. If I already know how to do it in Excel, I will do it in Excel instead of automating it, even though it takes me a lot of time. What if it doesn't work out and I won't have enough time to invest? They didn't understand the time-benefit ratio, but KPIs (key performance indicators) helped us make them use the automation tools." (I3 – Big 4.1). As the interviewees' answers show, the employee was one of the most important actors in the automation process, because without their acceptance, this process would not have been possible. Also, another important actor is the management who takes various measures to show people the benefits of using automation tools.

While some of the interviewees consider that the employees represented the main obstacle to the automation process, other interviewees would put the tax authorities in first place. In this regard, one of the respondents mentioned the following: "The main obstacle in the attempt to automate accounting processes, I believe, was the state which took late measures regarding the elimination of bureaucracy and the development of automation processes at the level of financial-administrative units. It took a pandemic to speed up the automation of systems used by administrative units and to adopt measures or procedures for remote work." (I5 – Non-Big 4.3). Nowadays, the Romanian tax authorities are much more digitalized and there is no longer a need for firms to present themselves with physical documents in their offices. Almost all aspects relating to tax authorities (such as tax returns, financial statements, various requests) are sent through their online platforms and via the single contact form. Currently, all companies are obliged to register in the Private Virtual Space (SPV) to communicate with the tax authorities, so the state itself is no longer considered an obstacle in the automation process, but can be considered an actor that participated in the change brought about by automation in the accounting industry. However, one of the interviewees considers that tax regulations still represent an obstacle. "[…] One of the obstacles I think was represented by tax regulations due to the lack of predictability and complex requirements" (I9 – Non-Big 4.6). Furthermore, for certain companies, the cost of automation tools represented an obstacle in the automation process, while for others the lack of dedicated resources or the systems utilized represented other impediments. Also, as stated by one of the Big 4 interviewees, the size of the company can be considered an obstacle. "I would say as my boss would say. This company is like a giant boat. Any movement happens with difficulty. A ship moves harder than a speedboat. The automation process is a long-term process […] and an obstacle could be the size of the company, because there are many approval processes." (I10 - Big 4.4).

In short, the accounting profession has been positively influenced by automation, but not as much as professionals in this industry expected. As the interviewees explained, the main benefits of automating accounting processes have been cost reduction, higher delivery speed to clients, decreased document processing time, and the diminution of the risk of human error. Moreover, the Covid-19 pandemic played a significant role in the accounting automation process. The majority of respondents consider that, at the level of the accounting industry, things were accelerated by the pandemic, changing the clients' way of working and pushing the tax authorities to develop their own automation processes. As presented, the change in the accounting industry determined by automation processes encountered some difficulties at the company level. In this regard, a portion of the interviewees consider that the human was the main obstacle in the automation process (clients and employees), while other interviewees consider that other impediments were related to the initial cost of the investment in automation tools, tax authorities, legislation, the lack of dedicated resources, and the company size. Several actors have been identified as part of the change driven by automation up to the present: market competition, accounting systems, the young accountant, the Covid-19 pandemic, employees, company management, clients, and tax authorities.

4.2 The degree of automation and professionals' perspectives

Nowadays, a large part of accounting processes are performed automatically, but some of them are still performed manually by employees. To ascertain the level of automation in the accounting industry, the interviewees were asked to what extent accounting processes are automated within the companies they work for. Regarding the bookkeeping part (recording transactions in the accounting software), one of the interviewees provided the following answer: "The degree of automation depends on how structured the accounting firm is compared to the flexibility it offers its clients. We are flexible regarding the client's accounting software, the reporting format, the reporting language, the way they send us documents. It heavily depends on how flexible or rigid the accounting firm is and the missions it has in relation to its client." (I1 – Non-Big 4.1). As explained above, the level of automation cannot be measured with certainty by companies, because it depends on many factors like those highlighted. However, another interviewee estimated the level of automation as follows: "At the moment, accounting processes are somewhere around 20%-30% automated, and we hope to reach 50% in the future. We are talking about the part of processing payments, receipts, bank journals." (I6 – Non-Big 4.4). While for a Non-Big 4 company, accounting processes are 20-30% automated, for a Big 4 company, these processes are 80%-90% automated as explained below by one of the interviewees. "Being part of a multinational company and having technologization as a target, the processes are largely automated starting with data entry, payment uploads, OCR of invoices which are recorded automatically, […], so we are about 80%-90% automated." (I10 – Big 4.4).

The OCR solution for purchase invoices is also utilized by other companies, as reported by the interviewees. In total, four respondents mentioned the use of OCR in the automation of accounting processes. Also, other solutions such as RPA or various automation tools are

utilized by accounting firms to record transactions in accounting systems, as presented by one of the interviewees. "[…] For the part of recording transactions in accounting systems we use specialized tools and RPA; we have designed robots to extract data from different files and in various formats and we prepare data for upload into various accounting systems/ERPs, just a click away." (I9 – Non-Big 4.6). As presented, OCR and RPA solutions are widely used at the level of accounting firms for the automation process of recording accounting documents. In addition, Excel import files or other automation tools are also widely used. Moreover, some of the interviewees mentioned that primary data already comes semi-automated from the client, when the client uses the same accounting system as the accounting firm, especially for the issued invoices part.

In relation to the tax bodies, the majority of the interviewees specified that reports can be extracted from the utilized accounting systems, which are mostly designed for the Romanian tax legislation, and employees merely verify the figures. Other interviewees stated that reporting to tax authorities is done through internally developed tools. Conversely, other companies still prepare these reports manually. In this regard, one of the respondents explained: "We are working on preparing the automated drafting of financial statements; we have a tool made through a pilot project that we are trying to optimize, but now it is mostly done manually. Tax returns are not yet automated; they will be automated in the second stage of this pilot project I was talking about. We are trying some automation for the SAF-T declaration as well." [I6 – Non-Big 4.4]. Regarding the new requirements in relation to tax authorities, such as SAF-T reporting and RO e-factura, one of the interviewees mentioned the following: "In the context of the new requirements, tax authorities compel companies to automate. We are talking about the new SAF-T reporting. Without a reporting system, it is almost impossible to do the declaration manually or it consumes a lot of time. In this field, almost all companies opt for automation. Only firms that have to issue the electronic invoice and have very few documents monthly have the option to do them manually. Otherwise, with the digitalization of the tax authorities' system, companies will be forced to automate all processes related to tax statements, because the volume is much higher than in the past." (I4 – Big 4.2). Currently, in Romania, only large and medium-sized companies have been required to submit the SAF-T declaration to the tax bodies, while small and micro companies reported starting with 2025. Also, the electronic invoice is mandatory only for certain companies at this moment. As presented by the interviewee above, the new requirements of the tax authorities will force all companies to automate at some point, because otherwise it will be almost impossible for them to prepare such reports manually, which requires a lot of time.

Outsourced accounting service firms also prepare ad-hoc reports for their clients upon request. Depending on the type of reporting, accountants can spend hours preparing the package. As with reporting to tax bodies, some of the interviewees mentioned that the reporting part to their clients is done automatically or semi-automatically. In this sense, one of the interviewees explained: "For standard reports we have semi-automated processes, some based on macros, others on Alteryx, others on machine learning software or Power BI, but it depends on the client and what can be automated. We try to automate as much as

possible on a case-by-case basis and depending on the benefit, but also on future cost recovery." (I4 – Big 4.2). On the other hand, some of the interviewees stated that reporting to clients is done manually. The degree of automation, as presented by the interviewee above, also depends on future cost recovery, and this could be one of the reasons why some companies do not invest in automation processes and still prepare reports manually.

Besides the initial investment costs and all other factors explained above, another important aspect is related to how automation is managed within companies, but more importantly, to the main actors involved in this process. The majority of the interviewees argued that the automation process is a mix, but the idea generally comes from the management, being perceived as the initiator of this process. In this direction, one of the respondents presented: "It is a mix between employees, a dedicated team, but it clearly starts from the management who established the strategy of accelerated digitalization of the company, who is also the sponsor. Management promotes and funds the digitalization strategy. We also have an automation department that works together with the IT department which analyzes the necessary resources, data security that goes through automation solutions. […] Automation started with internal resources and punctually with external providers […]. It also depends on the employees. It is useless to have an automation department if the employees do not use the solutions. So, everyone is involved, including employees, because it depends on them if the solutions work, they are the ones who provide feedback." (I1 – Non-Big 4.1). From what is presented above, it can be deduced that at least five actors are involved in the automation process. The first is the management who takes the necessary steps in achieving the automation goal. The second is represented by the dedicated team, more precisely the automation team that provides the automation solution. The third is the IT department which helps the automation team to analyze factors such as data security and necessary resources. The fourth actor could be represented by the external provider who offers certain solutions in case the automation department needs them. The last actor, but not necessarily the last, is the accounting employee who accepts the automation solutions, utilizes them, and provides feedback related to the solution's functionality. As the interviewed individuals presented, this process is similar in other eight companies as well.

Another factor that can initiate the automation process can be the way accounting professionals perceive automation. If automation is perceived as an opportunity, then accounting processes can become more automated. On the other hand, if automation is perceived as a threat, accounting processes will not be as automated, or the process occurs at a slower speed. Generally, the interviewees considered that automation represents an opportunity for everyone involved, as stated by one of the respondents: "It is always an opportunity, because the accountant's work itself is in continuous transformation; we are moving from data operator to analyst who can understand and interpret. This change brings satisfaction and an increased level of well-being that you are no longer a little mouse, but a consultant who analyzes whether certain indicators have increased or decreased. Automation goes hand in hand with the transformation of accounting jobs." (I10 – Big 4.4). The optimistic vision of the accounting professional will always say opportunity because automation can bring with it a certain level of satisfaction to the employees and of course,

to the company in general. This is because the work accountants did in the past is set aside and their role will become more relevant and valuable to clients. Although for some accounting professionals automation is certainly an opportunity, for others there is a certain level of hesitation. In this regard, one of the interviewees explained: "I think it depends on which boat you are on. It is obvious that people, old-school accountants, who still rely on debit-credit and document processing will be eliminated slowly, slowly. […] For this type of accountant, it will be a challenge to continue. For companies like us, I see it as a great opportunity […]." (I6 – Non-Big 4.4). A similar idea was also supported by other interviewees: "In any field, automation is both an opportunity and a threat. The opportunity is for those who embrace it and see its advantages, and the threat is for those who say: 'here I will die, I will change nothing'. For a mindset where you keep your energy stagnant, the game is a losing one. It depends on which side you are on. Automation in accounting makes no difference compared to other fields." (I2 – Non-Big 4.2). "I would say opportunity. I think for the accounting profession in general, digitalization is an opportunity to stop doing repetitive and boring things and to do things that truly bring value. On the other hand, I believe the skills you need must change, you have to go through a transformation process. From the feedback I have received, I see that 5 or 6 out of 10 people want to change, and the rest simply do not have the power or the desire to do it. That is why it could be a threat. If we get out of the shell, we are talking about opportunity." (I3 – Big 4.1). As accounting professionals have presented, automation can represent both an opportunity and a threat, depending on the accountant's personality and their desire for change. The opportunity is for those who embrace it and see its advantages, and the threat is for those who believe that change is a huge and difficult-to-overcome challenge.

From the last paragraph above, it can be observed that the changes brought about by automation in the accounting profession also require changes at the level of employee competencies. This is an essential element that companies request in present-day practice. Regarding this problem, the interviewees consider that skills such as digital ones, analytical thinking, the ability to ask questions, communication skills, presentation skills, synthesis power, foreign languages, openness, acceptance, and availability are just a small part of what new graduates should possess. Moreover, one of the interviewees added: "I think the right graduates for today's accounting practice should possess skills like patience, reaction speed, organization, responsibility, […], attention to detail, observation, reliability." (I5 – Non-Big 4.3). On the other hand, because the new generation will no longer have as much contact with source documents, a part of the interviewees consider that more knowledge in the accounting area is necessary so that those new to the field can get to understand and interpret data. In this regard, one of the respondents explained: "I would say it is clear that if they want to work in accounting, they must have accounting knowledge. It will be more difficult to learn everything on the job without this knowledge. New employees want rapid growth, they no longer want to be juniors and then accounting knowledge is necessary." (I4 – Big 4.2). Regarding this aspect, universities should play an essential role in preparing students for practice, not only for knowledge in the accounting area, but also for digital and analytical knowledge in general. In relation to this aspect, one of the interviewees

explained: "I think we need much more digital knowledge, if not programming languages, at least data and analytics areas, SQL, Python. You cannot generalize to a large mass of people, but at least at certain faculties there should be more courses related to the technical area. In the soft skills area, there is a need for better communication, effective data presentation, negotiation courses, teamwork courses, collaboration in various environments, it is a suite of elements that makes us more adaptable to this change. There should be better collaboration between universities, employers and professional organizations that contribute with training […]." (I3 – Big 4.1).

Automation can be successfully implemented if employees possess the necessary skills to work with the new tools. As presented, there are also other important actors who can contribute to the change brought about by automation in the accounting industry. Firstly, universities and professional organizations would play an important role by teaching students intensive accounting courses, digital and analytical courses. Another important actor is the employer who should organize different trainings to prepare their employees, especially the junior ones.

In brief, accounting processes are not completely automated by accounting firms in Romania, neither from the perspective of bookkeeping (recording accounting transactions) nor from the reporting perspective. As presented, Big 4 accounting firms have a higher potential to invest in automation tools, as they are part of multinational groups that target technologization, unlike smaller or local companies. Depending on the systems utilized and how automation is managed within companies, processes can be automated, semi-automated or performed manually. For automation tools, accounting firms in Romania use OCR, alongside RPA, AI or other automation tools developed internally or externally. Moreover, as the interviewees presented, automation is managed by approximately five main actors within the company: management, the automation department, the IT department, external providers of automation tools, and employees. Regarding the significance of accounting automation, the majority of the interviewed individuals consider that it represents an opportunity for the industry, because it drives people to achieve more valuable things. On the other hand, automation represents a threat for employees who accept changes with difficulty, and these changes are also related to the skills employees should possess. As the interviewees suggested, the most important skills are technical ones, but also soft ones. Regarding technical competencies, universities and professional organizations would play an important role in preparing students for contemporary accounting practice.

4.3 The future of the accounting profession

According to the World Economic Forum (2020) report, data entry, accounting, and payroll jobs rank first and second in the top ten categories of redundant jobs that could disappear due to or thanks to automation in the future. To see if this issue is also applicable at the level of Romanian accountants, the interviewees were asked if they consider that accounting practitioners will be replaced by robots in the near future and if their jobs will still exist due to or because of automation, especially for data entry. In this regard, one of the respondents

expressed their opinion as follows: "A large part of accountants' work will be taken over by robots, but to say that humans will be replaced by robots is an exaggeration. There must be a critical eye. Quantitatively speaking, accounting will be automated, but qualitatively speaking, accounting will still be done by humans." (I6 – Non-Big 4.4). As explained above, humans are still needed for qualitative tasks, even if quantitative tasks will be taken over by robots. Also, humans should work closely with robots to provide accurate data and necessary information for decision making. In relation to this aspect, another interviewee explained: "We shouldn't think about the replacement option, but rather the option of a good collaboration between accountants and robots regarding the division of work tasks. The robots' tasks should be validated by accountants." (I7 – Non-Big 4.5). The human accountant will still be the one who validates the robots' work, because robots do not yet have the capacity to analyze and interpret data.

If data entry jobs will be taken over by robots, people will have more time to focus on things that bring added value to the company and especially to the clients. Regarding this aspect, the interviewees consider that many other jobs will be available for accountants in the near future. For example, one of the respondents mentioned: "[…] Their jobs will transform, they will no longer be data processors; instead, they will do analysis, interpretation, consulting and recommendations, things that accountants do not have time to do now. The role of the accountant will consist of measurement, evaluation, management, knowledge and control." (I1 – Non-Big 4.1). Although accountants will no longer be the ones entering data into accounting, as presented above, many other opportunities will be available to them, so the accounting profession will not disappear. It will continue to exist, but under other roles or different positions within the company.

However, a significant aspect remains questionable. How can an entry-level accountant gain experience in data analysis and interpretation if they skip the data entry part and will no longer have contact with documents to understand the nature of a certain transaction? Regarding this problem, one of the interviewees answered: "[…] The data entry part will need to be known and will be a sort of 'multiplication table' for the accountant. If you do not know how to do it, you will have a problem. The role of the school will have to be stronger so that people come with the 'multiplication table' already learned and step into more difficult things. I think good people will have a future in this field." (I6 – Non Big 4.4). Professionals consider that accounting education should play an essential role in preparing students for what accounting means today and accounting in the future. A more solid theoretical foundation is needed so that those working in this field know how to analyze and interpret data. The idea that universities should provide students with a more solid theoretical foundation was also supported by two other interviewees. However, according to the respondents, there will be other ways of learning for young accountants. In this regard, one of the interviewees explained: "I know it is possible. Graduates will start to be more advanced than before. The way I see things, some very intense preparations must be made and for a much longer period. There should be capture and shadow programs where people who have had contact with primary documents can supervise the new ones in the field, so that they can adapt to this work." (I3 – Big 4.1). Employers will also play an

important role in preparing new employees in terms of ensuring more intensive training programs. In this way, but also through the contribution of universities, the transition from traditional accounting to more modern accounting will be possible, especially since firms target the highest level of automation possible. In relation to this problem, one of the interviewees concluded: "The objective is to give the machine everything it can do and leave to the human what they can do better. If something a human does could be done better by a machine, I will give the machine to do it. The goal is to increase the degree of process automation while surrounding myself with happier people, fulfilled with what they do. We work on this every day." (I2 – Non-Big 4.2).

In summary, the accounting profession will change in the future, so that accountants are more appreciated by clients. The role of accountants will change, but the change is seen as a good thing by professionals, because people will have more time to focus on relevant aspects, leaving mundane tasks to robots. Universities and employers will have a very important role in preparing new juniors through more intensive theoretical accounting courses, but also more intensive training programs. The goal of every company is to increase the level of automation in the future and to offer people the opportunity to assert themselves in relation to clients.

5. Discussions and conclusions

The conducted research examined the impact of automation on the financial-accounting profession within the ten largest outsourced accounting service firms in Romania, utilizing Actor-Network Theory (ANT) as a theoretical foundation (Callon M., 1986; Law J., 2007; and Latour B., 2005) to interpret the results, alongside a qualitative approach based on semi-structured interviews. In this regard, the present study examined the existing impact of automation on the accounting profession, the level of automation regarding data entry and reporting, its significance, the newly required competencies, and the future of the accounting profession concerning job losses, as well as the opportunities that will emerge as a result of the profession's automation. Throughout the transformation process, various actors were identified as exerting either a positive or a negative influence on this process. The initiator of the process, as presented by the interviewees, is the company's management, which identifies the problem and seeks solutions. Alongside the automation and IT departments, as well as external providers of automation tools, management works to achieve the solution for streamlining accountants' work. As the obtained results indicated, over time, a variety of obstacles were encountered. Automation solutions require rigorous rules from the clients of accounting firms because the information should already be in an electronic format, a matter that was not previously accepted by all clients. Additionally, the bureaucracy of the tax authorities represented another obstacle. During the Covid-19 pandemic, when office work shifted remotely, these two obstacles were overcome, yet other obstacles still persist. Some of the interviewees argued that employees have a significant impact on the transformation process, as it depends on them whether the automation solution is utilized or not. In this regard, management must find solutions to demonstrate the benefits of using new technologies to the personnel. Another portion of the interviewees

considers that the lack of dedicated human resources could be another impediment in the automation process. Moreover, the continuously changing tax legislation influences the automation process, as automation solutions are rule-based, and companies must frequently update their systems. Another issue relates to the level of costs, particularly concerning the initial investment, which presents uncertainties regarding future recovery; consequently, some companies refrain from investing precisely for this reason. Summarizing, the actor network related to process transformation is developed for the majority of companies, but for it to remain stable, each must play its role in this direction (Law, 2007).

In Romania, automation has positively influenced the accounting profession regarding the reduction of working time, the decrease of long-term costs, faster delivery of results to clients, and more accurate data with fewer errors; however, it has also involved costs at the company level. These costs are primarily related to the initial investment in automation tools. Nevertheless, the study participants consider that automation has affected the accounting profession but has not yet reached its maximum capacity. According to the interviewees, there are currently many activities in the accounting field that are not automated and are still performed manually by humans. For instance, the data entry part is automated only to a certain extent, especially for rule-based activities, such as recording and issuing invoices, and recording bank and cash transactions. For purchase invoices, some companies utilize OCR solutions to read data and RPA solutions or Excel files to process and import the data into the accounting system. Reports relating to tax authorities, such as tax returns or financial statements, are automatically generated by the accounting software used by some companies, while other companies still prepare these reports manually. Client reporting is performed manually by a portion of the participating companies, while others utilize AI tools such as Power BI or Alteryx. The degree of process automation depends to some extent on the company's size and its potential to invest in technology. However, according to the obtained results, to remain in the market, companies must invest in technology (Jylhä și Syynimaa, 2019).

The study participants consider that automation represents an opportunity for contemporary accountants, even though for some who are unwilling to accept certain changes and challenges, it might represent a threat. To succeed in this field, new accountants should possess skills that were not absolutely necessary until now. According to the results, regarding soft skills, accountants should be effective communicators and speakers; they should possess the ability to ask questions, synthesis power, acceptance, openness, availability, reaction speed, time management, attention to detail, observation, patience, and responsibility. Also, regarding technical skills, the interviewees consider that the new employee should possess more digital skills and advanced accounting knowledge, considering that the data entry part will largely be performed by robots. In this regard, universities and professional organizations will play an essential role in preparing students for contemporary accounting practice. Accountants must know how to interpret and analyze data, as they will no longer be mere data processors, but rather consultants and analysts (Mohammad et al., 2020) [19]. The interviewees believe that accountants' jobs will not disappear, and humans will not be replaced by robots. Instead, their tasks will be divided

between humans and robots. Humans should validate the robots' work, as well as analyze and interpret certain transactions—tasks that cannot be performed by robots. These findings are consistent with the results of previous studies asserting that accountants' jobs will transform, and humans will still be necessary for specific activities (Kokina și Blanchette, 2019; Holmes și Douglass, 2021) [1];[2]. The goal of all companies is to automate everything that can be automated and to leave humans with tasks that can bring added value for themselves, the company, and the clients.

The conclusions of the present study have several practical implications. Firstly, the results suggest that, to remain competitive, companies should invest in new technologies and automate as much as possible. As the results indicate, companies unwilling to achieve this will no longer exist in the market, because clients will no longer agree to pay them. Another aspect relates to the young generation of accountants whose affinity is the digital world (PwC, 2020), and practices such as paperwork do not define them. For this reason, companies unwilling to invest will no longer have either employees or clients. Secondly, the research findings suggest that universities and professional organizations should adapt their curriculum with new digital modules and offer more intensive accounting courses. This is due to the fact that future employees will no longer be in contact with source documents as before, and therefore, they must enter the workforce with very strong accounting skills and knowledge to understand, analyze, and interpret data.

This study contributes to the specialized accounting literature in the following ways. Firstly, while other studies focus their attention on the effects of digitalization on firms providing accounting services in various European countries (Jylhä și Syynimaa, 2019; Januszewski et al., 2021) [20], the aim of the present study is to identify the impact of digitalization, and especially automation, on accounting firms in Romania. The rationale for selecting this context is related to the DESI index ranking (EU Commission, 2022), where Romania ranked last even in 2023. In this regard, the intention was to observe the extent to which this ranking is applicable at the level of the accounting profession. As the results demonstrate, the largest accounting firms are largely digitalized and automated, but not to the extent that accounting professionals would have desired. Secondly, while other authors employ various approaches to identify the impact of digitalization on the accounting profession—such as literature reviews (Ciurea și Man, 2020; Gușe și Mangiuc, 2022) [21] or questionnaires—in researching the Romanian context, this paper utilizes a qualitative approach based on semi-structured interviews.

The findings of the study should be considered in light of certain limitations. Firstly, the number of interviewees is limited to ten, and the interviewed companies are the largest in Romania. To understand the difference between these companies and other smaller firms regarding the automation of accounting processes and their potential to invest in new technologies, future studies could invite participants from other accounting firms as well. Additionally, this study utilizes a qualitative approach based on semi-structured interviews and does not provide quantitative data. Future studies could identify the impact of

automation on the accounting profession by employing a quantitative approach based on questionnaires or other types of empirical investigations.

References

[1] Kokina, J. și Blanchette, S. (2019). Early evidence of digital labour in accounting: Innovation with Robotic Process Automation, International Journal of Accounting Information Systems, 35, p. 100431.

[2] Holmes, A. F., și Douglass, A. (2021). Artificial Intelligence: Reshaping the Accounting Profession and the Disruption to Accounting Education. Journal of Emerging Technologies in Accounting, 19(1), 53-68.

[3] Dilla, W. N., și Raschke, R. L. (2015). Data visualization for fraud detection: Practice implications and a call for future research. International Journal of Accounting Information Systems, 16, 1-22.

[4] Ma, D., Fisher, R., și Nesbit, T. (2021). Cloud-based client accounting and small and medium accounting practices: Adoption and impact. International Journal of Accounting Information Systems, 41, p. 100513.

[5] Macovei, A. G., Cojocari, A., și DASCĂ, I. (2021). Generation Y And Z Perception Of Digitalization In The Accounting Field. European Journal of Accounting, Finance & Business, 16(26), 21-26.

[6] Keenoy, C. L. (1958). The impact of automation on the field of accounting. Accounting Review, 230-236.

[7] Kerremans, M., Theunisse, H., și Van Overloop, G. (1991). Impact of automation on cost accounting. Accounting and Business Research, 21(82), 147-155.

[8] Wilson, R. A., și Sangster, A. (1992). The automation of accounting practice. Journal of Information Technology, 7(2), 65-75.

[9] Dongre. N., Pandey .A. și Gupta, O., P. (2020). Artificial Intelligence in Accounting: Opportunities & Challenges. Journal of Xi'an University of Architecture & Technology. ISSN No: 1006- 7930 7(5).

[10] Cohen, M., și Rozario, A. (2019). Exploring the use of robotic process automation (RPA) in substantive audit procedures. The CPA Journal, 89(7), 49-53

[11] Albu, C. N., Albu, N., și Hoffmann, S. (2021). The Westernisation of a financial reporting enforcement system in an emerging economy. Accounting and Business Research, 51(3), 271-297.

[12] Albu, N., Albu, C. N., Bunea, Ş., Calu, D. A., și Girbina, M. M. (2011). A story about IAS/IFRS implementation in Romania. Journal of Accounting in Emerging Economies.

[13] Lowe A. (2004) Postsocial Relations: Toward a performative view of accounting knowledge. Accounting, Auditing & Accountability Journal, 17 (4): 604-08.

[14] Hsieh, H. F., și Shannon, S. E. (2005). Three approaches to qualitative content analysis. Qualitative health research, 15(9), 1277-1288.

[15] O'Connell, B., Ciccotosto, S., și De Lange, P. (2014). Understanding the application of ActorNetwork Theory in the process of accounting change.

[16] Albu, N., Albu, C. N., și Gray, S. J. (2020, July). Institutional factors and the impact of international financial reporting standards: the Central and Eastern European experience. In Accounting Forum. 44(3), 184-214. Routledge.

[17] Murro, E. V. B., și Beuren, I. M. (2016). Actor networks in specialized accounting inspection: an analysis in the light of the Actor-Network Theory. Revista Brasileira de Gestão de Negócios, 18, 633-657.

[18] Alsharari, N. M. (2016). The diffusion of accounting innovations in the new public sector as influenced by IMF reforms: actor-network theory. International Journal of Actor-Network Theory and Technological Innovation (IJANTTI), 8(4), 26-51.

[19] Mohammad, S. J., Hamad, A. K., Borgi, H., Thu, P. A., Sial, M. S., și Alhadidi, A. A. (2020). How Artificial Intelligence Changes the Future of Accounting Industry. International Journal of Economics and Business Administration, 8(3), 478-488.

[20] Januszewski, A., Kujawski, J., și Buchalska-Sugajska, N. (2021). Benefits of and obstacles to RPA implementation in accounting firms. Procedia Computer Science, 192, 4672-4680.

[21] Guşe, G. R., și Mangiuc, M. D. (2022). Digital transformation in Romanian accounting practice and education: Impact and perspectives. Amfiteatru Economic, 24(59), 252-267.

Bibliography

1. Bogasiu, I., și Ardeleanu, N. (2021). Advantages and disadvantages of digitalisation in accounting. EIRP Proceedings, 16(1).

2. Callon M. (1986). Some elements of a sociology of translation: domestication of the scallops and the fishermen of St. Brieuc Bay. In: Law J, editor. Power, Action, and Belief: A New Sociology of Knowledge? London: Routledge; p. 196-223.

3.Cobzaru, P. (2018), Scurta istorie a contabilitatii, Available at: https://expertissimo.ro/scurtaistoriecontabilitatii/#:~:text=In%20Romania%20profesia%20contabila%20este%20puternic%20legiferata%20de,in%20cee%20ace%20priveste%20raspunderea%20juridical%20 a%20creditorilor%29 (Accessed:14.03.2026).

4. Deloitte (2021). Raportarea SAF-T, obligatorie pentru marii contribuabili de la 1 ianuarie 2022. Ce presupune implementarea? Available at: https://www2.deloitte.com/ro/ro/pages/tax/articles/raportarea-saf-t-obligatorie-pentru-marii-contribuabili-de-la-1-ianuarie2022-ce-presupune-implementarea.html (Accessed: 19.04.2026).

5. Feleagă, L., și Feleagă, N. (2016). Romania. Shifting to IFRS: The Case of Romania. In: Bensadon, D., Praquin, N. (eds) IFRS in a Global World: International and Critical Perspectives on Accounting, Springer, Cham. 393-404

6. Jylhä, T., și Syynimaa, N. (2019). The Effects of Digitalisation on Accounting Service Companies. In International Conference on Enterprise Information Systems. SCITEPRESS Science And Technology Publications.

7. Law J. (2007). Actor Network Theory and the Material Semiotics. Editor: Bryan S. Turner

8. Latour B. (2005). Reassembling the Social: An Introduction to Actor Network Theory. Oxford: Oxford University Press.

9. Popa, A. F. și Sova, R., A. Is the Romanian Accountancy Profession Ready for the Future? Yes! Available at: https://www.ifac.org/knowledge-gateway/developing-accountancyprofession/discussion/romanian-accountancy-profession-ready-future-yes (Accessed: 14.02.2026).

10. PwC (2021). Depre SAF-T, Available at: https://www.pwc.ro/ro/pwc-romania-digital/taxtechnology/saf-t.html (Accessed: 14.03.2026).

11.Shidaganti, G., Salil, S., Anand, P., și Jadhav, V. (2021, August). Robotic Process Automation with AI and OCR to Improve Business Process. In 2021 Second International Conference on Electronics and Sustainable Communication Systems (ICESC) (pp. 1612-1618). IEEE.

12.World Economic Forum (2020). The Future of Jobs Report 2020. Available at: https://www.weforum.org/reports/the-future-of-jobs-report-2020/in-full/country-andindustry-profiles (Accessed: 05.12.2025). https://www.weforum.org/focus/fourth-industrial-revolution

ADAPTIVE MULTI-OBJECTIVE OPTIMIZATION OF DEEP GROOVE BALL BEARINGS FOR HYDROGEN COMPRESSOR APPLICATIONS USING DYNAMIC CROSSOVER AND MUTATION PROBABILITIES

Prasun BHATTACHARJEE[1]

Somenath BHATTACHARYA[2]

Abstract

Deep groove ball bearings (DGBBs) used in hydrogen compressor systems operate under high loads, leading to elevated Hertzian contact stress and frictional torque. Optimal bearing design is therefore essential to enhance load capacity and operational efficiency. This study presents a multi-objective optimization approach for DGBBs considering basic dynamic load rating, Hertzian contact stress, and frictional torque. The objective is to maximize dynamic load rating while minimizing contact stress and torque. A customized adaptive genetic algorithm based on the NSGA-II framework is developed. Unlike conventional methods, crossover and mutation probabilities are dynamically varied during the optimization process. This adaptive strategy improves the balance between exploration and exploitation. Key design variables include ball diameter, number of balls, and bearing geometry. The model is evaluated under realistic loading conditions relevant to hydrogen compressor applications. Results obtained using static genetic parameters show limited Pareto front diversity. In contrast, the adaptive approach generates a wider and more uniformly distributed Pareto front. Improved convergence and better spread of solutions are observed. Significant reductions in Hertzian stress and frictional torque are achieved. Simultaneously, higher dynamic load ratings are obtained. The adaptive algorithm effectively avoids premature convergence. It provides a broader set of optimal design solutions. This enhances decision-making flexibility in bearing design. The proposed method demonstrates strong potential for high-load applications. It offers a robust framework for advanced bearing optimization. The study contributes to improved performance and reliability of DGBBs in energy systems.

Keywords: Adaptive genetic algorithm, Deep groove ball bearing, Dynamic load rating, Frictional torque, Hertzian contact stress, Hydrogen compressor systems.

JEL Classification: C61, C63, L93, Q42

[1] PhD, Jadavpur University, India, prasunbhatta@gmail.com
[2] PhD, Jadavpur University, India, snb_ju@yahoo.com

1. Introduction

The growing global demand for energy, coupled with the gradual depletion of fossil fuel reserves, has accelerated the transition toward sustainable and alternative energy systems. This transition has been further intensified by geopolitical uncertainties, particularly in major oil-producing regions such as the Middle East, where conflicts and supply disruptions have introduced significant volatility in energy availability and pricing. Such instability has exposed the limitations of fossil fuel–dependent systems and has underscored the urgent need for reliable, efficient, and low-carbon energy solutions. Among the various alternatives, hydrogen-based energy systems have emerged as a promising pathway for achieving long-term energy sustainability [1].

Hydrogen compressor systems play a vital role in the hydrogen energy infrastructure by enabling high-pressure storage and transportation. These systems operate under severe mechanical conditions characterized by high cyclic loads, elevated pressures, and continuous operation. Under such demanding environments, the reliability and performance of mechanical components, particularly rolling element bearings, become critical. Deep groove ball bearings (DGBBs), owing to their simple design, versatility, and capability to support combined loading conditions, are widely used in such applications. However, their performance under high-load and high-stress conditions requires careful optimization [2].

The behavior of DGBBs in such environments is governed by three key performance parameters: basic dynamic load rating, Hertzian contact stress, and frictional torque. The dynamic load rating determines the load-carrying capacity and fatigue life of the bearing, while Hertzian contact stress governs the localized stress distribution at the contact interface between rolling elements and raceways. Excessive contact stress can lead to fatigue failure mechanisms such as spalling and subsurface cracking. Frictional torque, on the other hand, directly influences energy efficiency and thermal characteristics, with higher torque leading to increased power loss and heat generation. The simultaneous consideration of these parameters results in a complex multi-objective design problem due to their inherently conflicting nature [3].

Recent advancements in bearing design have increasingly relied on computational optimization techniques to address such challenges. Various metaheuristic algorithms, including genetic algorithms, particle swarm optimization, whale optimization, and moth flame optimization, have been successfully applied to improve bearing performance. These approaches have demonstrated significant improvements in dynamic load capacity, frictional power loss, and lubrication characteristics, particularly in the design of hybrid bearings with ceramic rolling elements. Additionally, the integration of artificial intelligence techniques has enabled the optimization of renewable energy systems, including wind turbine components, where bearing performance plays a crucial role in system efficiency and reliability [4].

Several studies have also explored the enhancement of static and dynamic capacities of rolling element bearings through intelligent optimization strategies, considering multiple performance criteria simultaneously. The application of multi-objective optimization frameworks has provided valuable insights into the trade-offs between load capacity, stress distribution, and frictional behavior. However, most of these studies have employed conventional implementations of evolutionary algorithms with fixed crossover and mutation probabilities [5].

The use of static genetic parameters often limits the effectiveness of the optimization process, as it may lead to premature convergence and insufficient exploration of the design space. This limitation becomes more pronounced in complex engineering problems involving nonlinear interactions among design variables and conflicting objectives. To overcome these challenges, adaptive optimization techniques have been proposed, in which algorithmic parameters are dynamically adjusted during the optimization process to improve search efficiency [6] [7].

In this context, the present study proposes an adaptive multi-objective optimization framework for the design of deep groove ball bearings operating under high-load conditions representative of hydrogen compressor applications. The approach is based on the NSGA-II algorithm, with dynamically varying crossover and mutation probabilities to enhance both exploration and exploitation capabilities. The optimization problem is formulated with the objective of maximizing the basic dynamic load rating while minimizing Hertzian contact stress and frictional torque.

Key design variables, including ball diameter, number of rolling elements, and bearing geometry parameters, are considered under realistic operating conditions. A comparative analysis is performed between the proposed adaptive approach and conventional static-parameter genetic algorithms. The results demonstrate that the adaptive method yields a more diverse and well-distributed Pareto front, providing improved trade-offs among the governing performance parameters.

The proposed framework offers a robust and efficient approach for the optimal design of deep groove ball bearings in high-load applications. By integrating adaptive evolutionary algorithms with fundamental principles of rolling contact mechanics, the study contributes to the development of advanced bearing systems suitable for emerging hydrogen-based energy infrastructures. The findings are expected to support the broader transition toward sustainable energy systems in the face of fossil fuel depletion and geopolitical uncertainty.

2. Literature Review

The design and optimization of rolling element bearings have attracted significant attention due to their critical role in mechanical and energy systems. Traditional bearing design approaches are largely based on empirical relations and standardized formulations, which, although reliable, often fail to capture the complex interactions between geometric parameters, loading conditions, and performance characteristics. As a result, modern research has increasingly focused on computational and optimization-based techniques to enhance bearing performance.

Early studies in this domain primarily addressed the estimation of dynamic load rating and fatigue life using classical formulations based on rolling contact fatigue theory. These approaches provided a foundation for understanding bearing performance but were limited in their ability to address multi-parameter interactions. Subsequent research introduced numerical methods to evaluate contact stress, lubrication regimes, and frictional behavior, thereby improving the predictive capability of bearing models [8].

With the advancement of computational intelligence, metaheuristic optimization techniques have been widely adopted for bearing design. Genetic algorithms (GA) have been extensively used to optimize bearing parameters such as ball diameter, number of rolling elements, and internal geometry to improve load-carrying capacity and fatigue life [8]. Particle swarm optimization (PSO) and other swarm-based techniques have also been applied to minimize frictional losses and enhance lubrication performance. More recent approaches, including whale optimization and moth flame optimization, have demonstrated improved convergence characteristics in solving complex bearing design problems [9].

Significant progress has also been made in the optimization of hybrid bearings incorporating ceramic rolling elements, particularly for applications involving electrical insulation and high-speed operation. These studies have shown that advanced optimization techniques can effectively enhance both static and dynamic load capacities while reducing frictional power loss and improving elastohydrodynamic lubrication characteristics [10]. Furthermore, the application of multi-objective optimization frameworks has enabled simultaneous consideration of conflicting performance parameters, such as load capacity, contact stress, and frictional torque, leading to more balanced and efficient bearing designs [11] .

In parallel, optimization techniques have been successfully applied to renewable energy systems, particularly in the design of wind turbine components. These studies have highlighted the importance of bearing performance in improving overall system efficiency and reliability. Multi-objective optimization approaches have been used to minimize generation cost, maximize energy output, and improve component durability under varying environmental conditions [12].

Despite these advancements, most existing studies rely on conventional implementations of evolutionary algorithms with fixed crossover and mutation probabilities. While these

approaches have demonstrated effectiveness in generating optimal solutions, they often suffer from limitations such as premature convergence and reduced diversity of the Pareto front. Static parameter settings restrict the algorithm's ability to adapt to different stages of the optimization process, leading to suboptimal exploration of the design space.

To address these limitations, recent research has explored adaptive and self-tuning optimization strategies, where genetic parameters are dynamically adjusted during the search process. These approaches enhance the balance between exploration and exploitation, resulting in improved convergence and diversity of solutions [9]. However, the application of such adaptive strategies to the multi-objective optimization of deep groove ball bearings, particularly in the context of hydrogen compressor systems, remains limited.

Therefore, there exists a research gap in developing an adaptive multi-objective optimization framework that integrates bearing mechanics with dynamic genetic operators to achieve improved performance under high-load conditions. The present study aims to address this gap by proposing a customized adaptive NSGA-II approach for optimizing deep groove ball bearing design considering dynamic load rating, Hertzian contact stress, and frictional torque.

3. Methodology

3.1. Problem Formulation

The design of deep groove ball bearings (DGBBs) for high-load applications involves the simultaneous consideration of multiple conflicting performance parameters. In the present study, the optimization problem is formulated to enhance bearing performance under operating conditions representative of hydrogen compressor systems. The primary objective is to achieve an optimal balance between load-carrying capacity, contact stress, and frictional losses.

The optimization problem is defined with three principal objectives: maximization of the basic dynamic load rating, and minimization of Hertzian contact stress and frictional torque. These objectives are inherently conflicting in nature. An increase in load-carrying capacity generally requires modifications in bearing geometry, such as increased ball diameter or number of rolling elements, which may lead to higher frictional torque. Similarly, reduction in contact stress often demands design adjustments that influence both load capacity and torque characteristics.

3.2 Design Variables and Constraints

The optimization process considers key geometric parameters of the bearing, including ball diameter, number of rolling elements, and mean diameter. These variables directly influence load distribution, contact mechanics, and frictional behavior. The design is subjected to a set of physical and geometric constraints to ensure feasibility. The equivalent dynamic load acting on the bearing must remain within the permissible load-carrying capacity. Additionally, the contact stress is restricted below an allowable limit to prevent premature fatigue failure. Geometric constraints are also imposed to maintain feasible bearing dimensions and proper assembly conditions. The equivalent dynamic load is evaluated by considering both radial and axial components of loading, ensuring realistic representation of operating conditions. These constraints collectively ensure that the optimized solutions are not only mathematically optimal but also physically realizable [13] [14].

3.3 Mathematical Modeling

The dynamic load rating is evaluated based on standard bearing design relations, which relate the load capacity to geometric parameters such as ball diameter and number of rolling elements. Hertzian contact stress is calculated using classical contact mechanics theory, considering the load distribution among rolling elements and the resulting contact ellipse. Frictional torque is estimated as a function of load, bearing geometry, and frictional characteristics, providing a measure of energy loss within the system. These models are integrated into the optimization framework to evaluate the performance of each candidate solution during the evolutionary process [15] [16].

3.4 Adaptive Multi-Objective Optimization Approach

To solve the formulated multi-objective problem, an adaptive version of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is employed. Unlike conventional implementations, where crossover and mutation probabilities remain constant, the present approach introduces dynamically varying genetic parameters to enhance the search efficiency [17] [18].

The adaptive mechanism is designed to improve the balance between exploration and exploitation during the optimization process. In the initial stages, higher mutation probabilities are employed to encourage exploration of the design space and avoid premature convergence. As the algorithm progresses, mutation is gradually reduced while crossover becomes more dominant, facilitating convergence toward optimal regions of the solution space [19] [20].

This adaptive strategy enables the algorithm to effectively navigate the complex, nonlinear design space associated with bearing optimization, resulting in improved diversity and convergence of the Pareto-optimal solutions.

3.5 Solution Procedure

The optimization process begins with the initialization of a population of candidate bearing designs, each defined by a set of design variables. For each individual, the objective functions are evaluated using the mathematical models described earlier. The population is then ranked based on non-dominated sorting, and a crowding distance measure is used to preserve diversity. Selection, crossover, and mutation operations are applied to generate new candidate solutions. The crossover and mutation probabilities are dynamically adjusted at each generation according to the adaptive strategy. This process is repeated iteratively until a predefined convergence criterion is satisfied [21] [22].

3.6 Performance Evaluation

The performance of the proposed adaptive optimization approach is assessed by comparing the obtained Pareto front with that generated using conventional static genetic parameters. The comparison focuses on the spread, diversity, and convergence of solutions, as well as the improvement in key performance parameters such as dynamic load rating, contact stress, and frictional torque.

4. Results and Discussion

The performance of the proposed adaptive multi-objective optimization approach is evaluated through a comparative analysis with the conventional NSGA-II algorithm employing static crossover and mutation probabilities. The comparison is based on the characteristics of the obtained Pareto fronts in terms of their distribution, extent, and the trade-off relationships among dynamic load rating, Hertzian contact stress, and frictional torque.

The Pareto front generated using static genetic parameters exhibits a nonlinear but uneven distribution of solutions. A clear trade-off is observed in which an increase in dynamic load rating is associated with a reduction in Hertzian contact stress, which is consistent with fundamental bearing mechanics, as higher load capacity generally results from improved load distribution and increased contact area. The frictional torque shows a relatively small variation within the range of approximately 0.015 kN·m to 0.017 kN·m. However, the distribution of solutions is predominantly concentrated within an intermediate region, with only a limited number of solutions extending toward higher dynamic load ratings. In this case, the dynamic load rating reaches approximately 140–150 kN, while the Hertzian contact stress varies between about 1.0×10^4 MPa and 1.7×10^4 MPa. The clustering of solutions indicates that the static genetic algorithm has a limited ability to explore the full design space and tends to converge prematurely to a restricted set of solutions.

In contrast, the Pareto front obtained using dynamically varying crossover and mutation probabilities demonstrates a significantly improved distribution and extent of solutions. The

adaptive approach enables a broader exploration of the design space, particularly toward higher dynamic load ratings, which extend up to approximately 180–200 kN. Correspondingly, the Hertzian contact stress is reduced in the high-capacity region, with values approaching approximately 1.0×10^4 MPa to 1.65×10^4 MPa. The frictional torque remains within a narrow and controlled range of approximately 0.0153 kN·m to 0.0156 kN·m, indicating that the improvement in load-carrying capacity and reduction in contact stress are achieved without a significant increase in frictional losses. The Pareto front in this case is more continuous and uniformly distributed, providing a smoother transition between different design configurations and enabling a more comprehensive representation of the trade-off among the objective functions.

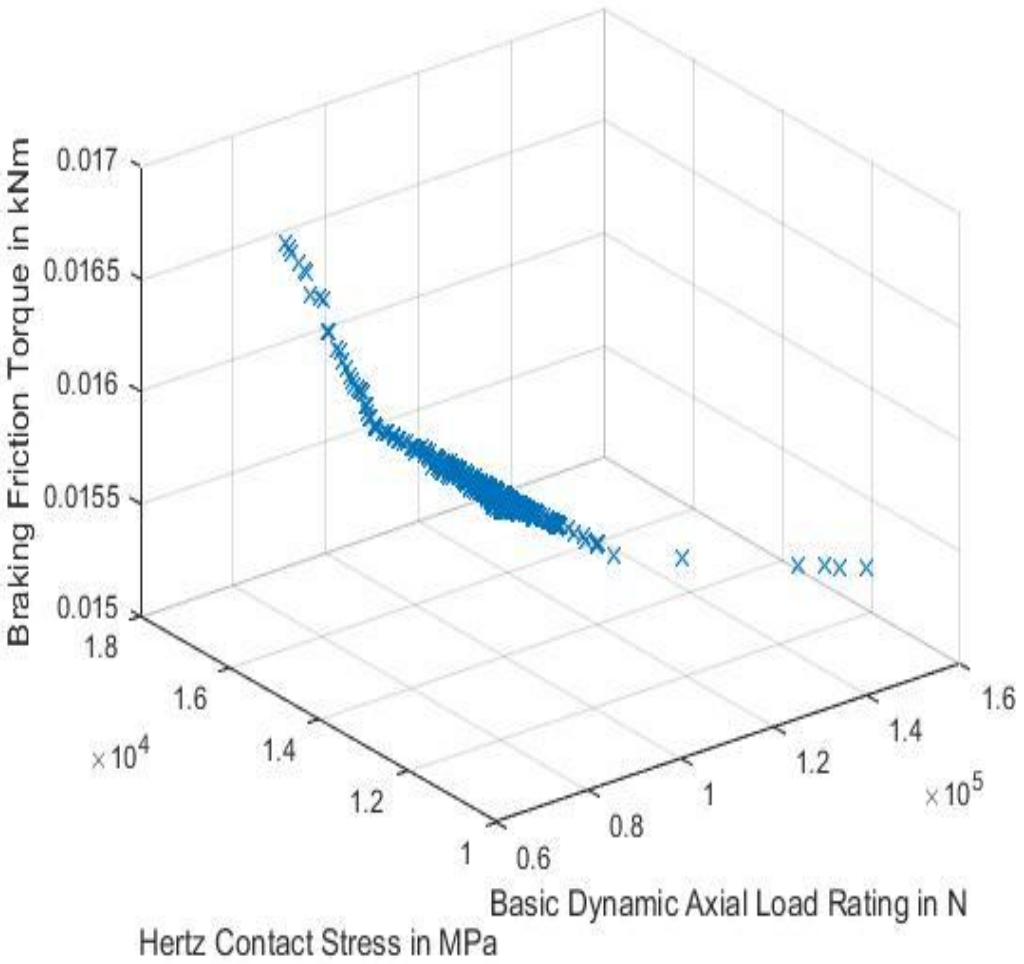


Figure 1. Pareto front obtained using NSGA-II with static crossover and mutation probabilities

The improvement observed in the adaptive approach can be attributed to the dynamic adjustment of crossover and mutation probabilities during the optimization process. In the early stages, higher mutation rates facilitate exploration of the design space, allowing the algorithm to identify diverse candidate solutions. As the optimization progresses, the reduction in mutation probability and increased influence of crossover enhance convergence toward optimal regions. This adaptive balance between exploration and exploitation prevents premature convergence and improves the overall quality and diversity of the obtained solutions.

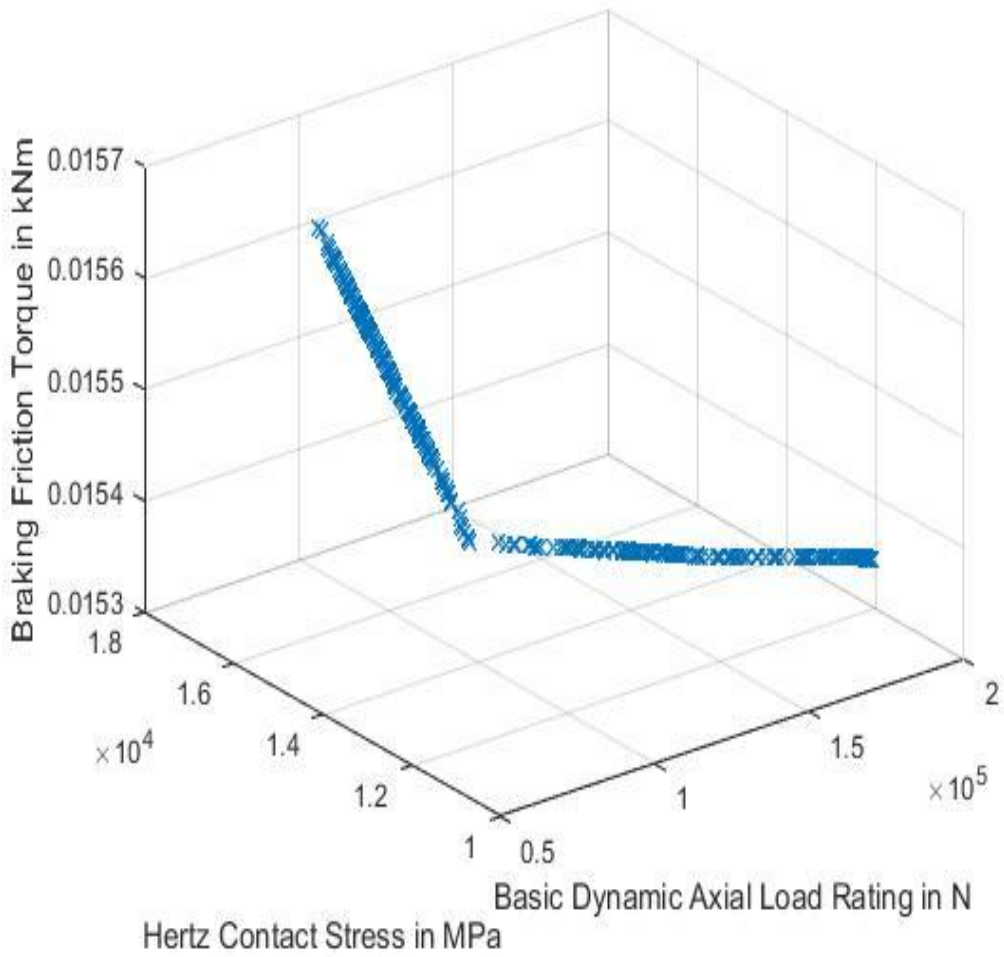


Figure 2. Pareto front obtained using NSGA-II with proposed adaptive crossover and mutation probabilities

From an engineering perspective, the adaptive optimization approach provides a wider range of feasible design solutions for deep groove ball bearings operating under high-load conditions. The extension of the dynamic load rating range, along with the reduction in

Hertzian contact stress, contributes to improved fatigue life and reliability of the bearing. At the same time, the relatively stable and controlled frictional torque ensures that energy efficiency and thermal performance are not adversely affected. The improved Pareto front thus offers greater flexibility in selecting optimal bearing configurations based on specific performance requirements.

Overall, the results demonstrate that the proposed adaptive multi-objective optimization framework significantly enhances the exploration capability and convergence behavior of the genetic algorithm. The method produces a more diverse and well-distributed set of Pareto-optimal solutions, extending the achievable design space and providing improved trade-offs among dynamic load rating, Hertzian contact stress, and frictional torque.

5. Conclusions

In this study, an adaptive multi-objective optimization framework has been developed for the design of deep groove ball bearings operating under high-load conditions relevant to hydrogen compressor systems [23] [24]. The problem was formulated by simultaneously considering three critical and conflicting performance parameters, namely dynamic load rating, Hertzian contact stress, and frictional torque. The objective was to enhance load-carrying capacity while reducing contact stress and maintaining acceptable frictional behavior, thereby improving overall bearing performance and reliability. A comparative analysis between conventional static genetic parameters and the proposed adaptive approach clearly demonstrates the advantages of dynamically varying crossover and mutation probabilities [25] [26]. The Pareto front obtained using static parameters exhibits a limited spread with noticeable clustering of solutions, indicating restricted exploration of the design space and a tendency toward premature convergence. In contrast, the adaptive approach produces a more extended and uniformly distributed Pareto front, enabling improved coverage of both intermediate and extreme design regions.

The adaptive optimization framework successfully extends the achievable dynamic load rating from approximately 140–150 kN in the static case to nearly 180–200 kN, while simultaneously reducing Hertzian contact stress in the higher capacity region. Importantly, this improvement is achieved without significant variation in frictional torque, which remains within a narrow and controlled range. This demonstrates that the proposed method is capable of identifying superior design configurations that offer a better balance among load capacity, stress distribution, and frictional performance. The enhanced performance of the adaptive approach is attributed to its ability to balance exploration and exploitation during the optimization process. Higher mutation rates in the early stages allow effective exploration of the design space, while gradual reduction in mutation and increased crossover facilitate convergence toward optimal solutions. This dynamic adjustment prevents premature convergence and improves both the diversity and quality of the obtained

Pareto-optimal solutions. From an engineering standpoint, the results indicate that the adaptive framework provides a broader and more practical set of design alternatives for deep groove ball bearings in high-load applications. The reduction in Hertzian contact stress contributes to improved fatigue life, while the increased dynamic load rating enhances load-carrying capacity. The controlled frictional torque ensures that efficiency and thermal considerations remain within acceptable limits. These improvements are particularly relevant for hydrogen compressor systems, where bearings are subjected to demanding operating conditions.

Overall, the proposed adaptive multi-objective optimization approach offers a robust and efficient methodology for bearing design, integrating fundamental contact mechanics with advanced evolutionary algorithms. The study demonstrates that dynamic control of genetic parameters can significantly enhance optimization performance and expand the feasible design space. The findings provide valuable insights for the development of high-performance bearing systems and can be extended to other engineering applications involving complex multi-objective optimization problem.

Acknowledgment

The authors gratefully acknowledge the academic environment and research support provided by Jadavpur University, Kolkata, which facilitated the successful completion of this work. The authors also express their sincere gratitude to colleagues and students for their valuable discussions and constructive suggestions during the course of this research. The computational resources and technical support utilized in this study are also duly acknowledged.

References

[1] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "A Comparative Analysis of Genetic Algorithm and Moth Flame Optimization Algorithm for Multi-Criteria Design Optimization of Wind Turbine Generator Bearing," ADBU Journal of Engineering Technology, vol. 10, no. 4, 2021.

[2] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Multi-Objective Design Optimization of Deep Groove Ball Bearing for Wind Turbine Generator," International Journal of Design Engineering, 2022.

[3] T. Harris, J. H. Rumbarger and C. P. Butterfield, "Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life," 2009.

[4] A. Duggirala, R. K. Jana, R. V. Shesu and P. Bhattacharjee, "Design optimization of deep groove ball bearings using crowding distance particle swarm optimization," Sādhanā, vol. 43, no. 1, 2018.

[5] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "A Comparative Study of Dynamic Approaches for Allocating Crossover and Mutation Ratios for Genetic Algorithm-based Optimization of Wind Power Generation Cost in Jafrabad Region in India," in Proceedings of International Conference on “Recent Advancements in Science, Engineering & Technology, and Management", Jaipur, India, 2021.

[6] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "A Novel Artificial Intelligence Technique for Enhancing the Annual Profit of Wind Farm," in 27th International Conference on Information Technology (IVUS 2022), Kaunas, Lithuania, 2022.

[7] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "An Enhanced Genetic Algorithm for Annual Profit Maximization of Wind Farm," Journal of Information Systems & Operations Management, vol. 15, no. 2, 2021.

[8] T. Bruce, H. Long and R. S. Dwyer-Joyce, "Dynamic modelling of wind turbine gearbox bearing loading during transient events," IET Renewable Power Generation, vol. 9, no. 7, p. 821–830, 2015.

[9] I. Chakraborty, V. Kumar, S. B. Nair and R. Tiwari, "Rolling element bearing design through genetic algorithms," Engineering Optimization, vol. 35, no. 6, pp. 649-659, 2003.

[10] W. Changsen, Analysis of Rolling Element Bearings, Mechanical Engineering Publications Ltd, London, 1991.

[11] S. Gupta, R. Tiwari and S. B. Nair, "Multi-objective design optimisation of rolling bearings using genetic algorithms," Mechanism and Machine Theory, vol. 42, no. 10, p. 1418–1443, 2007.

[12] ZWZ Wafangdian Bearing Group Corp., "ZWZ Wind Power Bearing," [Online]. Available: http://www.zwz-bearing.com/zwzwz-eng/product/bearingproduct/ZWZzcyb/ZWZ%20Wind%20Power%20Bearing%20Catalogue.pdf. [Accessed 20 March 2021].

[13] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Amplifying the Financial Sustainability of a Wind Farm near the Coast of Gujarat with an Augmented Genetic Algorithm," in International Symposium on Information & Communication Technology 2022, Greater Noida, India, 2022.

[14] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "An Improved Genetic Algorithm for Yearly Profit Maximization of Wind Power Generation System," in The 31st ACM SIGDA University Demonstration, New York, USA, 2021.

[15] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Boosting the annual profit of an offshore wind farm in India with a bio-inspired meta-heuristic scheme," Environmental Challenges, vol. 9, p. 100642, 2022.

[16] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Design Optimization of Cam in Computer-Aided Simulation Applications using Taguchi's Experimentation Method," International Journal of Electrical and Computer System Design, 2021.

[17] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Expanding the Financial Profitability of an Indian Wind Power Generation System with Artificial Intelligence-Assisted Meta-heuristic Process," in ICRDSTEM-2022: 1st International Conference on Recent Development in Science, Technology, Engineering & Management, Bengaluru, India, 2022.

[18] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Improving the Yearly Profit of Wind Farm with Artificial Intelligence Technique," Mindanao Journal of Science and Technology, vol. 20, no. 2, pp. 174-189, 2022.

[19] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Multi-Objective Design Optimization of Wind Turbine Blade Bearing," Invertis Journal of Science & Technology, vol. 14, no. 3, pp. 114-121, 2021.

[20] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Optimizing Offshore Wind Power Generation Cost in India," in Third New England Chapter of AIS (NEAIS) Conference, Boston, Massachusetts, 2021.

[21] P. J. Blau, L. R. Walker, H. Xu, R. J. Parten, J. Qu and T. Geer, "Wear Analysis of Wind Turbine Gearbox Bearings," Office of Scientific and Technical Information (OSTI), 2010.

[22] R. K. Jana and P. Bhattacharjee, "A multi-objective genetic algorithm for design optimisation of simple and double harmonic motion cams," International Journal of Design Engineering, vol. 7, no. 2, pp. 77-91, 2017.

[23] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "A Relative Analysis of Genetic Algorithm and Binary Particle Swarm Optimization for Finding the Optimal Cost of Wind Power Generation in Tirumala Area of India," ITM Web of Conferences, p. 03016, 2021.

[24] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "A Relative Assessment of Genetic Algorithm and Binary Particle Swarm Optimization Algorithm for

Maximizing the Annual Profit of an Indian Offshore Wind Farm," in Second International Conference on Applied Engineering and Natural Sciences, Konya, Turkey, 2022.

[25] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Maximizing the Yearly Profit of an Indian Nearshore Wind Farm," in First International Conference on Applied Engineering and Natural Sciences, Konya, Turkey, 2021.

[26] P. Bhattacharjee, R. K. Jana and S. Bhattacharya, "Realizing The Optimal Wind Power Generation Cost in Kayathar Region of India," in International Conference on Information, Communication and Multimedia Technology - 2021 (ICICMT - 2021), Madurai, 2021.

Bibliography

Bhattacharjee, P., Bhattacharya, S., & Karmakar, A. (2025, April). A novel dynamic probability assignment in NSGA-II for enhanced multi-objective optimization of 60NiTi bearings in spacecraft applications. In Proceedings of the 4th International Conference on Scientific and Innovative Studies (ICSIS 2025).

Bhattacharjee, P., & Bhattacharya, S. (2025). Improving wind energy's economic efficiency in Digha, West Bengal, India: A metaheuristic optimization method employing genetic algorithms and particle swarm optimization. Journal of Information Systems & Operations Management, 19(2), 49–62.

Bhattacharjee, P., & Bhattacharya, S. (2025, April). Harnessing coastal winds: Metaheuristic optimization of onshore wind power costs in Digha, West Bengal. In Proceedings of the 3rd International Conference on Trends in Advanced Research (ICTAR 2025).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). A comparative analysis of genetic algorithm and moth flame optimization algorithm for multi-criteria design optimization of wind turbine generator bearing. ADBU Journal of Engineering Technology, 10(4).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). A comparative study of dynamic approaches for allocating crossover and mutation ratios for genetic algorithm-based optimization of wind power generation cost in Jafrabad region in India. In Proceedings of International Conference on Recent Advancements in Science, Engineering & Technology, and Management (Jaipur, India).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). A relative analysis of genetic algorithm and binary particle swarm optimization for finding the optimal cost of wind power generation in Tirumala area of India. ITM Web of Conferences, 03016.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). An enhanced genetic algorithm for annual profit maximization of wind farm. Journal of Information Systems & Operations Management, 15(2).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). An improved genetic algorithm for yearly profit maximization of wind power generation system. In The 31st ACM SIGDA University Demonstration (New York, USA).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). Design optimization of cam in computer-aided simulation applications using Taguchi's experimentation method. International Journal of Electrical and Computer System Design.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). Maximizing the yearly profit of an Indian nearshore wind farm. In First International Conference on Applied Engineering and Natural Sciences (Konya, Turkey).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). Multi-objective design optimization of wind turbine blade bearing. Invertis Journal of Science & Technology, 14(3), 114–121.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). Optimizing offshore wind power generation cost in India. In Third New England Chapter of AIS (NEAIS) Conference (Boston, MA).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2021). Realizing the optimal wind power generation cost in Kayathar region of India. In International Conference on Information, Communication and Multimedia Technology (ICICMT 2021) (Madurai).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). A novel artificial intelligence technique for enhancing the annual profit of wind farm. In 27th International Conference on Information Technology (IVUS 2022) (Kaunas, Lithuania).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Amplifying the financial sustainability of a wind farm near the coast of Gujarat with an augmented genetic algorithm. In International Symposium on Information & Communication Technology 2022 (Greater Noida, India).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Boosting the annual profit of an offshore wind farm in India with a bio-inspired meta-heuristic scheme. Environmental Challenges, 9, 100642.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Expanding the financial profitability of an Indian wind power generation system with artificial intelligence-

assisted meta-heuristic process. In ICRDSTEM-2022: 1st International Conference on Recent Development in Science, Technology, Engineering & Management (Bengaluru, India).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Improving the yearly profit of wind farm with artificial intelligence technique. Mindanao Journal of Science and Technology, 20(2), 174–189.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Multi-objective design optimization of deep groove ball bearing for wind turbine generator. International Journal of Design Engineering.

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). A relative assessment of genetic algorithm and binary particle swarm optimization algorithm for maximizing the annual profit of an Indian offshore wind farm. In Second International Conference on Applied Engineering and Natural Sciences (Konya, Turkey).

Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2025, July). Strengthening the static and dynamic load endurance of solar panel gearbox bearings for enhanced sustainability: A metaheuristic approach. In Proceedings of the 2nd Annual International Congress on Renewable Energy.

Blau, P. J., Walker, L. R., Xu, H., Parten, R. J., Qu, J., & Geer, T. (2010). Wear analysis of wind turbine gearbox bearings. Office of Scientific and Technical Information (OSTI).

Bruce, T., Long, H., & Dwyer-Joyce, R. S. (2015). Dynamic modelling of wind turbine gearbox bearing loading during transient events. IET Renewable Power Generation, 9(7), 821–830.

Chakraborty, I., Kumar, V., Nair, S. B., & Tiwari, R. (2003). Rolling element bearing design through genetic algorithms. Engineering Optimization, 35(6), 649–659.

Changsen, W. (1991). Analysis of rolling element bearings. Mechanical Engineering Publications.

Duggirala, A., Jana, R. K., Shesu, R. V., & Bhattacharjee, P. (2018). Design optimization of deep groove ball bearings using crowding distance particle swarm optimization. Sādhanā, 43(1).

Gupta, S., Tiwari, R., & Nair, S. B. (2007). Multi-objective design optimisation of rolling bearings using genetic algorithms. Mechanism and Machine Theory, 42(10), 1418–1443.

Harris, T., Rumbarger, J. H., & Butterfield, C. P. (2009). Wind turbine design guideline DG03: Yaw and pitch rolling bearing life.

Jana, R. K., & Bhattacharjee, P. (2017). A multi-objective genetic algorithm for design optimisation of simple and double harmonic motion cams. International Journal of Design Engineering, 7(2), 77–91.

Sen, S., & Bhattacharjee, P. (2025). Comparative analysis of genetic algorithm, particle swarm optimization, and simulated annealing for rooftop solar panel layout optimization in Indian cities. In Proceedings of the 8th International Conference on Applied Engineering and Natural Sciences (ICAENS 2025).

ZWZ Wafangdian Bearing Group Corp. (2021). ZWZ wind power bearing catalogue.

GAMIFICATION STRATEGIES TO INCREASE EMPLOYEE ENGAGEMENT INTO SUSTAINABILITY

Codruț Florin CRĂCIUN[1]
Paul-Tiberius COMAN[2]
Oana PREDA[3]
Nicoleta Rossela DUMITRU[4]

Abstract

Faced with a climatic crisis and economic pressure, companies are more and more involved into adopting sustainability strategies. Implementation of sustainability practices can become a global challenge, but for a real impact its crucial that employees are involved actively. Unfortunately, many organizations have difficulties motivating the workers to take part in such initiatives (Aguilera et al., 2021). This study explores the field of gamification and how to stimulate employee involvement into sustainability practices, transforming these initiatives into an attractive and interactive process. By integrating playful mechanism, such as rewards and real time feedback, organizations can increase the employee participation and consolidate sustainability culture among them (Aragón-Correa & Sharma, 2003). Our study aims to validate this if there is any potential impact of gamification over sustainability behaviours among employees for the Romanian labour market.

Keywords: *employee gamification, corporate sustainability, employee sustainability, internal marketing*

JEL classification: *Q01*

[1]Phd Sudent, Bucharest University of Economic Studies, Bucharest, Romania, craciuncodrut24@stud.ase.ro
[2] Phd Sudent, Bucharest University of Economic Studies, Bucharest, Romania, comanpaul13@stud.ase.ro
[3] Associate Professor PhD, Romanian-American University.oana.preda@rau.ro
[4]Associate Professor PhD, Romanian-American University, nicoleta.rossela.dumitru@rau.ro

1. Introduction

Sustainability represents an essential and social objective, which aims the development of all companies on the medium and long term premises. The three pillars of sustainability, the political, economical and environmental factors show that sustainability not only limits to an efficient strategy for the environment protection, on the contrary, it includes social and economic issues, which can influence both the companies and the community on a long run. (Maria Stancu, 2024)

For example, in 2024, the study named „Romanian attitude towards sustainability" emphasizes major changes in the consumers and employees behavior. In Romania, more than 50% of the employees stated that they wish their employers be much more involved in the environmental protection. This suggests that there is expected that the labour force implement sustainable policies.

Currently, international organisations such as UN and European Commission considers sustainability to be essential in the transition to a circular economy, emphasizing that the private sector has a major role in this process.

In order to understand better the importance of sustainability in the business environment, we can also consider the UN sustainable development goals, which boosts the organizations to implement policies that both reduce the environmental impact, and promote equitable and inclusive economic development.

2.Research objectives

Our first objective is to propose a basic theoretical framework regarding how organizations can involve their employees into corporate sustainability efforts through gamification.

A secondary objective covers the potential discovery of gamification strategies, ideas or applications in order to provide better employee engagement while increasing their loyalty to the brand because of its implications into good social and environmental practices meant to reduce production impact.

3.Issues addressed

The main issue addressed is a low engagement rate of employees regarding sustainability. In contrast they recognize the high importance regarding an organizational impact over society and environments (Norton et al., 2012). We suppose that in Romania the engagement rate is low too.

4.Theoretical framework

When we discuss about employees and sustainability it's important to raise our attention towards two dimensions: sustainability at the working space and sustainability affinity as a daily basis (after work). Workspace sustainability means when the organization offers a proper space with care for the working environment as a component regarding their ESG strategy. More on that, office design is planned accordingly with employee needs (Fauth &

Pieper, 2022). In a former paper (MATAC et al., 2024) one of the current work`s authors showed the role of accountants into ensuring legal compliance with corporate sustainability legislation.

Sustainability, from a point of view as a day to day behaviour is the case-scenario when people's behaviours are driven to a change in order to keep the consistency into being responsible with the medium. On the other side, ESG sustainability is even more focused on environment, social and governance which are the abbreviation components. The ESG term was discussed first time in 2004 în an United Nations Global Compact report that is no longer available on the official source but can be downloaded from some online archives. ESG thematics became more and more important into European space once the european Corporate Sustainability Directive was introduced into legislation (MATAC et al., 2024).

The first research decision to be made is to choose between researching employee engagement into sustainability within their current workspace (at a personal level) or employee engagement at corporate level aspects regarding the impact it produces for the environment, society at all and how it is managed. We believe that companies are used to follow the profit, workers to follow the personal gains and the intersection of both can result into following the synergy between these two for a social purpose.

We aim to analyze multiple gamification theories, application ideas regarding environmental and climate projects made by companies even before the Corporate Sustainability Reporting Directive (CE, 2024).

As climate change and environmental degradation become a pressing issue, companies have to adopt sustainable strategies in order to keep their customers and to avoid sanctions. Sustainability in business refers not only to reducing the impact on the environment, but also to the implementation of practices that meet the economic and social needs of organizations. However, for these practices to be effective, employees must be actively involved.

Many organizations are trying to implement green strategies but their employees are not always motivated to actively participate (Aragón-Correa, 1998). This is the context where gamification becomes an innovative approach transforming sustainability into an interactive and attractive process for employees (Aragón-Correa & Sharma, 2003). Gamification consists into introducing game elements such as rewards, challenges and feedback. That way, employees are encouraged to participate more actively into company`s green initiatives increasing short term commitment and forming an organizational culture for the long term (Aguilera et al., 2021).

5.Challenges of sustainable practices at work

Although the benefits of sustainability are obvious, the implementation of this practices faces a series of major challenges. In the following we will discuss each with academic support.

Resistance to change is a well known issue because many employees and managers are accustomed with the new sustainable technologies and practices, and the change may be perceived as an additional effort. (Michael Adelusola, 2024)

Lack of motivation might be another major obstacle, especially if it is the lack of a reward system for that employees adopting a sustainable behavior. Studies show that the moment the rewards are clear and direct, the employees are more motivated to actively participate at this process. (Oana, Cosman, 2024)

Another challenge is a lack of a clear framework for measuring the produced impact. It is very complicated to demonstrate the success of green initiatives without the support of a monitoring process system. (Aryamol et al, 2024)

6.How gamification can support sustainability initiatives

Gamification, by integrating the playing elements in the daily routine of employees, can seriously increase their involvement in sustainability initiatives. This type of approach changes sustainable behavior into an interesting and competitive game, which encourages employees to adopt new habits (Sorin Burlacu, 2020).

Leaderboard and badges can be used in order to give recognition and reward to those employees adopting sustainable behavior. Internal competitions between departments for reducing resource consumption are an efficient way of encouraging employees to adopt sustainable behavior.

Rewards for innovation are another scheme that can incentivize workers to get involved(Sarbat, I., Tasan, S.O., 2022). As a success example is it worth to mention Unilever who has implemented a system based on points in order to reduce the waste of water, and the results were impressive, a 20% cut in water consumption in the first year. This is an example of success where gamification has contributed to achieving a significant sustainable issue.

Lowensteyn et al. (2019) discovered several gamification tools useful for workspace sustainability. We noted several gamification techniques like:

- goals setting,
- leaderboards,
- awarding badges, c
- competing in challenges,
- generation of social influence.

7.Measuring the impact of gamification strategies on sustainability

In order to assess the efficiency of gamification strategies in promoting sustainability, it is imperative that we use the some relevant performance indicators that are aligned with the organization`s sustainability strategy.

Reducing resource consumption

This KPI measures the direct impact of sustainable activities on natural resources savings, such as water, energy and paper. For example, if a company implements a saving energy policy, time monitoring this consumption is essential in order to assess the success of the initiative. (Gupta, A. & Jangara, S., 2024)

Measuring the employees rate of participation to sustainable initiatives is another important KPI.

A gamification program can evaluate the number of employees attending competitions focused on reducing energy and recycled consumption.

It is crucial for the employees to give feedback concerning the gamification program efficiency. This may include anonymous surveys measuring both the employees motivation and satisfaction and regular assessments of progress (Xiao, H., et al., 2022). Studies from Central and Eastern Europe have emphasized that the companies adopting interactive measures, such as those based on gamification, can eventually reduce carbon footprint and achieve important savings in the resource consumption. This examples demonstrate the efficiency of gamification, as a tool used in promoting sustainability.

8.Sustainability of working spaces

Having a sustainable working space means having access to shared resources (Oswald & Zhao, 2020). Accordingly to Fauth & Pieper (2022) a sustainable office circles around physical, functional and psychological needs. Physical needs involves aspects regarding senses: visual confort, noise protection, spatial acoustic, climate comfort. We discovered in practice another physical need: ambiental scent as some offices as well as shopping centers are using air fresheners to influence the ambiance and establish emotional ties between the brand and employee (RAO & Jetti, 2020).

Regarding air fresheners and sprays, some studies showed they must be reduced as much as possible because usage of these devices has been linked with increased diseases, asthma attack and other health-issues, especially the ones with high emissivity of ultra fine particles (Karr et al., 2021). This being said, not any climate improvement is actually a sustainable measure but could be perceived as such by specific people while others may perceive it as a problematic concern.

The sustainability of a working space can be categorized to material, technological, informational needs as stated in Lowensteyn et al. (2019).

Other researches classified sustainability resources in relation with self and organization resulting into a group-level resource obtained through team work and by building social capital, organization-level resources by supporting traineeships, problem solving tools at an individual level and transformational leadership skills as a leader-level resource (Nielsen et al., 2010)

Having these into consideration we can define workspace sustainability as a set of needs employees have, all kind of resources they can use all with a final scope of well-being and at the same time for a higher productivity.

9.Employees and ESG sustainability

A higher level of sustainability takes place at the corporate level in relation with its stakeholders and all impacted individuals at a global scale at the same time.

A study referring to gamification principles aiming increased support in wellness shows evidence that gamification may increase long term participation among workers

(Lowensteyn et al. (2019)). Gamification strategies made employees stay supportive to the new changed behaviour even in the absence of financial incentivization. One possible limitation to their study is the subject of wellness itself. Individuals may be more concerned with their own state rather than a global impact produced by the activity of the company where they work. It is work to study how people feel and associate/disassociate with the corporation regarding medium impact.

10.Methodology or approach

Our methodology is based on literature review and mapping of current state for CSR, ESG, sustainability, gamification, pro-environmental organizations and applications of gamification in companies for their employees.

Based on the theoretical frameworks discovered, we designed a quantitative survey in order to collect information about how employees intend to engage into sustainability policies among their companies without and with gamification and what applications can integrate them better into such work activities.

For the data collection process we used LimeSurvey because it allowed us to use variables for question answers.

11.Results

Gamification can be a very powerful tool in promoting sustainability at work, because it can turn sustainable behavior into an interesting and competitive activity. By using interactive strategies, companies can higly motivate their employees to play an active part in the process of reducing the impact on environment, creating though significant economical and environmental benefits.

Our participant sample was composed of 150 respondents, having demographic and educational characteristics that provide a solid basis for analyzing behavioral intentions and receptivity to alternative methods of motivation. The occupations were extremely diverse: marketing, education, IT, medical fields, automotive, advertising, public administration, students, etc., situation that provides an interdisciplinary basis for our results interpretation.

The questionare consists of 41 questions, as following in the table.

1.Summary for Age	
under 18 years	0.00%
18-24 years	17.65%
25-34 years	39.71%
35-44 years	19.12%
45-54 years	19.12%
over 55 years	4.41%
2.Summary for Gender	
Male	36.76%

Female	63.24%
Other / Not answearing	0.00%
3.Summary for Marital Status	
Married	42.65%
Not married	55.88%
Divorced	1.47%
Widow	0.00%
4.Summary for Education(the highest level of education	
No studies	0.00%
Middle school education	0.00%
High School	7.35%
Bachelor	16.18%
Master s Degree	67.65%
PhD	8.82%
5.Summary for Residence	
Urban	89.71%
Rural	10.29%
6. What does sustainability mean? (select all that apply)	
Being mindful of the environment	94.12%
Social awareness	83.82%
Reduction in consumption due to production	69.12%
Using resources in a way that does not compromise the needs of future generations	91.18%
Promoting social and economic equity	58.82%
Creating sustainable and recyclable products	89.71%
Maximizing profit at any cost	4.41%
Rapid and unlimited consumption of resources	5.88%

Unlimited access to resources	4.41%
7. What field do you currently work in?	
Marketing	
University	
IT	
Hotels, restaurants and coffe shops	
Student	
Education	
Health	
International Affairs	
Psichology	
Economic	
Sales	
Advertising	
Research	
Human Resources	
Digital Marketing	
Game testing	
web development	
Customer service	
8. My company has a sustainability strategy	
Total disagreement	0.00%
Disagreement	4.41%
Neutral	45.59%
Agreement	27.94%
Total agreement	22.06%
9. My company's strategic decisions are hevily influenced by sustainability	
Total disagreement	1.47%
Disagreement	1.47%
Neutral	76.47%
Agreement	14.71%
Total agreement	5.88%

10. It is really important that the organization I belong to gets involved in social responsibility actions.	
Total disagreement	0.00%
Disagreement	8.82%
Neutral	5.88%
Agreement	41.18%
Total agreement	44.12%
11. Some social responsibility actions are pointless/useless.	
Total disagreement	19.12%
Disagreement	35.29%
Neutral	17.65%
Agreement	26.47%
Total agreement	1.47%
12. The company I work for is transparent about its impact on the environment, including when that impact is negative.	
Total disagreement	4.41%
Disagreement	8.82%
Neutral	27.94%
Agreement	38.24%
Total agreement	20.59%
13. Do you think rewards should be implemented for sustainable behavior?	
Yes	82.35%
No	11.76%
Don’t know	5.88%
14. How motivated would you be to participate in an internal competition that rewards sustainable behavior?	
Very little	2.94%
Little	7.35%
Neutral	41.18%
Much	33.82%
Very much	14.71%

15. Initiatives to introduce internal games or competitions can increase my colleagues' involvement in sustainability.	
Very little	0.00%
Little	4.41%
Neutral	36.76%
Much	39.71%
Very much	19.12%
16. My colleagues are involved in sustainability and social responsibility initiatives.	
Very little	4.41%
Little	7.35%
Neutral	55.88%
Much	17.65%
Very much	14.71%
17. The introduction of game elements (e.g., points, badges, rankings) would make sustainability more interesting for me.	
Very little	0.00%
Little	17.65%
Neutral	11.76%
Much	35.29%
Very much	35.29%
18. I would feel more motivated to adopt sustainable behaviors if I could track my progress in a fun or interactive way.	
Very little	7.35%
Little	11.76%
Neutral	17.65%
Much	44.12%
Very much	19.12%
19. Friendly competitions between departments can encourage the adoption of green practices.	
Very little	0.00%
Little	19.12%
Neutral	11.76%

Much	35.29%
Very much	33.82%
20. Internal platforms that transform sustainable actions into games can create a sense of community and responsibility.	
Very little	4.41%
Little	4.41%
Neutral	19.12%
Much	48.53%
Very much	23.53%
21. Public recognition through digital badges or diplomas motivates colleagues to participate in sustainable initiatives.	
Total disagreement	0.00%
Disagreement	16.18%
Neutral	17.65%
Agreement	58.82%
Total agreement	7.35%
22. An internal platform with sustainable missions and real-time feedback would encourage ongoing participation.	
Total disagreement	0.00%
Disagreement	5.88%
Neutral	11.76%
Agreement	66.18%
Total agreement	16.18%
23. Recycling of 3 items	
Yes	94.12%
No	5.88%
24. Using alternative transportation for a day	
Yes	89.71%
No	10.29%
25. Using the bike for a day	
Yes	64.71%
No	35.29%

26.Reducing paper consumption	
Yes	97.06%
No	2.94%
Select Yes/No regarding the sustainability activities you are willing to get involved in.	
27. Reuse of packaging	
Yes	76.47%
No	23.53%
28. Proposing a green project by email to management	
Yes	64.71%
No	35.29%
29. Identifying areas of energy waste	
Yes	61.76%
No	38.24%
30. Involvement in volunteer activities during the program	
Yes	72.06%
No	27.94%
31. Involvement in volunteer activities outside the program	
Yes	50.00%
No	50.00%
Would you be willing to participate in the games listed below?	
32. Participation in daily or weekly missions	
Yes	70.59%
No	29.41%
33. Completing eco tasks to receive badges	
Yes	70.59%
No	29.41%
34. Completing eco-tasks and participating in various activities to earn points and track them in a ranking of sustainable employees	
Yes	69.12%
No	30.88%

35. Role-playing games in the company regarding certain sustainability decisions	
Yes	66.18%
No	33.82%
36. Workshops on eco-themed drawing or painting	
Yes	61.76%
No	38.24%
37. Searching for "ESG treasures," for example, identifying areas of energy waste	
Yes	54.41%
No	45.59%
38. Enrollment in courses on environmental and social responsibility	
Yes	58.82%
No	41.18%
39. Participation in tests and examinations on ESG knowledge	
Yes	51.47%
No	48.53%
40. The challenge wheel (spinning an interactive wheel that will make a colleague perform a challenge, for example, not using paper for a day)	
Yes	85.29%
No	14.71%
41. If you had to choose between these companies to work for, which one would you choose?	
The company with a slightly higher salary	41.18%
Company more involved in social and environmental activities	5.88%
The company with a smaller environmental footprint	10.29%
The most financially stable company	42.65%

Source: Author's own work.

One of the queries was if “My company has a sustainability strategy” on by using the likert evaluation scale on 5 levels along with other questions Almost half of the respondents had a neutral position, suggesting uncertainty or lack of clear communication from the company on its sustainability strategy.

The dominance of "neutral" at 76% at the question “My company's strategic decisions are heavily influenced by sustainability” suggests that many respondents do not perceive a visible integration of sustainability into strategic business decisions or are not sure whether it is taken into account in management decisions. Maybe the entire decisional process is not transparent within the organization.

Other questions like “The company I work for is transparent about the impact it creates on the environment” had varied responses of agreement, disagreement and neutral therefore we could not find any semnificative data.

The only quality answers obtained from the survey are releated to specific activities of gamification that could lead to increased awareness and involvements into sustainability:

- 59% believe that the introduction of games or competitions would increase peer involvement.
- over 71% of respondents believe that points, scores, badges makes sustainability more interesting.
- 63% consider that possibility of progress tracking would help.
- 70% believe that challenges are a good way to initiate sustainable activities.

Participants are generally open to getting involved in sustainable actions, especially if they are integrated into the work schedule or involve minimal effort. Willingness drops significantly in the case of extra-curricular activities or activities involving a high degree of personal commitment.

We managed to obtain a ranking of *sustainability activities where employees are more interested* in based on their responses.

- Reduction of paper consumption: 97.06%
- Recycling 3 objects: 94.12%
- Using alternative transport for a day: 89.71%
- Reuse of packaging: 76.47%
- Involvement in voluntary activities during the program: 72,06%
- Cycling for a day: 64.71%
- Green project proposal by e-mail to management: 64.71%
- Identification of energy wasting areas: 61.76%
- Involvement in voluntary activities outside the program: 50,00%

Regarding *gamification*, we obtained from all the survey responses a ranking based on the answer percentages.

- Challenge Wheel (random challenges to colleagues by a spinning wheel): 85.29%
- Participation in daily or weekly missions: 70.59%

- Solving ecological tasks and receiving badges upon completion: 70.59%
- Completing ecological tasks and accumulating points to rank in a leaderboard: 69.12%
- Company role playing on sustainability decisions: 66.18%
- Drawing and painting workshops with ecological thematics: 61.76%
- Participating in lessons about environmental and social responsibility: 58.82%
- Searching for "ESG treasures" in organization (e.g. identifying energy waste areas): 54.41%
- Participation in ESG examinations for knowledges: 51.47%

The key information of the current study consists into many representations and perceptions that sustainability has in the black box of the employee - their mind. The more we dive in the research the more limits and issues arise and more research with various qualitative and quantitative tools is needed.

Not all employees fully understand what sustainability does, what is an ESG policy, how organizations impact the 3 pillars and why they have to find the optimal balance between profit and footprint.

Not all companies are transparent regarding their social-environmental impact even if the CSRD European directive will impact every kind of organization as it already started with big corporations and will continue until SMEs in 2026 (Matac et al, 2024).

The lack of transparency is not only external but also internal as lower level employees do not know how their activity is impacted by sustainability decisions.

12.Future research and limits

As stated in first part, it is necessary to examine the engagement rate of employees into sustainability practices in Romanian labour market. More than that, a transversal research on several years is a research must have project that is currently missing.

Before starting the data collection, we identified there are some barriers that could make employees unwilling to act in a sustainable manner. Some may think that a socially responsible policy might involve even more work to be done at the office. These barriers are hard to detect because respondents could present biased information and probably they will avoid expressing their real issues. Stating unpopular opinions regarding sustainability could make them look selfish. These barriers could be another field of research.

Another limit discovered during research is the relation between employee well-being and organizational performance because a low team climate is affecting overall likelihood to involve is sustainable practices within organization (Nielsen et al., 2010).

The majority presence of women (over 60%) in the sample may positively influence the openness towards sustainability values, in line with the literature that associates the female gender with a more pronounced inclination towards pro-social and environmental values.

Lastly, one of the most interesting limitations we discovered during data collection was regarding employees that work in more technical jobs or with an under average educational level because the most of them did not knew the meaning of such terms as “sustainability”

and "gamification". For us, the researches, these terms might become regular but there are categories of worker that have never interfered with them.

References

1. Adelusola, M. (2024). *Sustainable Business Practices: Overcoming Barriers and Leveraging Enablers for Organizational Adoption.*
2. Anjali Gupta, & JANGARA, S. (2024). *Green human resource management and work engagement: Linking HRM performance attributions. Sustainable Futures, 7.*
3. Cosman, O. (2024). *Sustenabilitatea, în top 3 priorități ale companiilor. Cum folosesc tehnologia pentru tranziția verde.*
4. Directive 2013/34/EU of the European Parliament and of the Council of 26 June 2013 on the Annual Financial Statements, Consolidated Financial Statements and Related Reports of Certain Types of Undertakings, Amending Directive 2006/43/EC of the European Parliament and of the Council and Repealing Council Directives 78/660/EEC and 83/349/EEC, L 182 Official Journal of the European Union 19 (2013).
5. European Commission. (2024). Corporate Sustainability Reporting. *https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en*
6. Irem Sarbat, & TASAN, S. O. (2022). *Ergonomic indicators: A proposal for sustainable process performance measurement in ergonomics.*
7. Nair, A. (2024). *Gamification in the Workplace: Evolution, Applications, and Implications.*
8. Roy, R., & Konwar, J. (2021*). Gamification: Ushering the Way to Workplace Happiness Via Discretionary Effort.*

Bibliography

Aguilera, R., Aragón-Correa, J. A., & Marano, V. (2021). *The corporate governance of environmental sustainability*. Journal of Management, 47(6), 1468–1497.

Aragón-Correa, J. A. (1998). *Strategic proactivity and firm approach to the natural environment.* Academy of Management Journal, 41(5), 556–567.

Aragón-Correa, J. A., & Sharma, S. (2003). *A contingent resource-based view of proactive corporate environmental strategy.* Academy of Management Review, 28(1), 71–88.

Aryamol, K. S., Kanagaraj, K., Nangan, S., Haponiuk, J. T., Okhawilai, M., Pandiaraj, S., Hanif, M. B., Alodhayb, A. N., Sabu, T., Thirumalaivasan, N., & Gopi, S. (2024). *Recent Advances of carbon Pathways for Sustainable Environment development*. Environmental Research, 250.

Burlacu, S. (2020). *Challenges of Sustainable Urban Development in the Context of Population Growth.* European Journal of Sustainable Development.

DuVernet, A., & Popp, E. (2014). *Gamification and workplace practices*. The Industrial-Organizational Psychologist, 52, 39–43.

Fauth, R., & Pieper, M. (2022). *Designing sustainable office spaces – how to combine workspace characteristics with sufficiency strategies*. IOP Conference Series: Earth and Environmental Science, 1078, 012032. https://doi.org/10.1088/1755-1315/1078/1/012032

Gamification strategies to increase employee engagement into sustainability. (n.d.). Google Docs. Retrieved April 15, 2025, from https://docs.google.com/document/u/0/d/1ns_0G5q8jDLJhRyZ25GUHkv59ODm0UvwHHCzC3BsOcE/edit?usp=embed_facebook

Gruenewald, H., Kneip, P., Kozica, A., Kenon, V., & Palsole, S. (2019). *The Use of Gamification in Workplace Learning to Encourage Employee Motivation and Engagement.* 557–575. https://doi.org/10.1002/9781119227793.ch29

Hu, X., Khan, S. M., Huang, S., Abbas, J., Badulescu, D., & Matei, M. C. (2022). *Employees' Green Enterprise Motivation and Green Creative Process Engagement and Their Impact on Green Creative Performance*. International Journal of Environmental Research and Public Health, 19(10).

Karr, G., Quivet, E., Ramel, M., & Nicolas, M. (2021). *Sprays and diffusers as indoor air fresheners: Exposure and health risk assessment based on measurements under realistic indoor conditions.* Indoor Air, 32. https://doi.org/10.1111/ina.12923

Koz, O. (2013). *Workplace gamification*. https://doi.org/10.13140/2.1.4057.4089

Landers, R., & Marin, S. (2021). *Redesigning Job Tasks and Work Itself Through Workplace Gamification* (pp. 63–89). https://doi.org/10.4324/9780429316722-6

Lim, W., Das, M., Sharma, W., Verma, A., & Kumra, R. (2024). *Gamification for sustainable consumption: A state-of-the-art overview and future agenda*. Business Strategy and the Environment, 34. https://doi.org/10.1002/bse.4021

Lowensteyn, I., Berberian, V., Berger, C., Costa, D., Joseph, L., & Grover, S. (2019). *The Sustainability of a Workplace Wellness Program That Incorporates Gamification Principles: Participant Engagement and Health Benefits After 2 Years.* American Journal of Health Promotion, 33, 850–858. https://doi.org/10.1177/0890117118823165

MATAC, L. M., PANTAZI, F., COMAN, P.-T., & BOLBOCEANU, M. (2024). *The Role of Expert Accountants in Ensuring Regulatory Compliance with Corporate Sustainability* Reporting in the European Union. CECCAR Business Review, 5(10), 2–6. https://doi.org/10.37945/cbr.2024.10.01

Nielsen, K., Randall, R., & Christensen, K. (2010). *Does training managers enhance the effects of implementing team-working? A longitudinal, mixed methods field study.* Human Relations - HUM RELAT, 63, 1719–1741. https://doi.org/10.1177/0018726710365004

Norton, T., Zacher, H., & Ashkanasy, N. (2012). *On the Importance of Pro-Environmental Organizational Climate for Employee Green Behavior.* Industrial and Organizational Psychology, 5, 503. https://doi.org/10.1111/j.1754-9434.2012.01487.x

Oswald, K., & Zhao, X. (2020). *What Is a Sustainable Coworking Space*? Sustainability, 12, 10547. https://doi.org/10.3390/su122410547

RAO, K., & Jetti, E. R. (2020). *Scent Marketing – Harnessing the Power of Scents in stimulating senses of Organized Retail Consumers and Em*ployees. International Journal of Innovative Science and Research Technology, 5, 575–584. https://doi.org/10.38124/IJISRT20SEP134

Stancu, M. (2024). *Sustenabilitatea este noua normalitate*. KPMG Survey of Sustainability Reporting 2024.

United Nations Global Compact. (2004). *Who Cares Wins: Connecting Financial Markets to a Changing World*. United Nations Department of Public Information. https://documents1.worldbank.org/curated/en/280911488968799581/pdf/113237-WP-WhoCaresWins-2004.pdf

LABOUR MIGRATION IN ROMANIA: CURRENT TRENDS AND CHALLENGES FOR 2026

Elena Raluca CRISTIAN [1]

Laura Georgeta BĂRĂGAN [2]

Abstract

The COVID-19 pandemic had a significant impact on labour mobility, both at the European level and worldwide, accelerating a series of structural changes taking place within labour markets. Romania, alongside other European Union member states, represents a particular case, as it continues to be one of the main exporters of labour within the European Union, while at the same time, over the past five years, it has become increasingly dependent on foreign workers, especially from non-EU countries.

This article aims to analyse labour migration and labour mobility in Romania in the post-pandemic period, focusing on two main directions: the migration of Romanian labour towards the European Union and the inflow of foreign workers (immigrants) into Romania, with particular attention given to workers from Nepal and other Asian countries.

The analysis is based on recent statistical data available up to March 2026 and seeks to highlight the economic, political and social implications of these trends, the imbalances observed on the labour market, as well as the public policy challenges Romania faces as a member state of the European Union.

The results of the study indicate that Romania is moving towards a paradoxical labour market model, characterised by the persistent emigration of its own workforce abroad, alongside a growing dependence on imported labour, particularly in sectors where highly qualified labour is not required.

Keywords: labour migration, labour mobility, post-pandemic labour market

JEL Classification: F22, J21, J61, O15, O52

1. Introduction

Labour migration has been a defining and relatively constant feature of the Romanian economy for more than two decades, particularly since the 1990s.

[1] Assistant Professor, PhD at the Romanian American University in Bucharest, Romania, email address: elena.raluca.cristian@rau.ro

[2] PhD, Lecturer at the Romanian American University in Bucharest, Romania, email address: laura.georgeta.baragan@rau.ro

Following Romania's accession to the European Union, the country experienced a broad, complex and far-reaching process of labour emigration, mainly directed towards Western European states such as Italy, Spain, Germany, the United Kingdom and France.

This phenomenon intensified after the COVID-19 pandemic, despite the temporary restrictions on labour mobility imposed during the period 2020–2021.

At the same time, in the post-pandemic context, Romania has increasingly faced labour shortages in several strategic or key economic sectors, including construction, manufacturing, agriculture, HORECA, transport, tourism and public food-related services.

The post-pandemic period has brought new challenges for the Romanian labour market. The gradual economic recovery of the country, combined with demographic decline in certain areas or regions, as well as the persistent emigration of Romanian workers, has amplified the demand for labour within the domestic economy.

As a result, Romania has begun to shift from being predominantly a labour-exporting country to becoming, at least partially, a labour-importing economy.

The growing presence of foreign workers, particularly from countries such as Nepal, Sri Lanka, India or Bangladesh, reflects this structural change.

The main objective of this article is to analyse labour migration and labour mobility in Romania after the COVID-19 pandemic, with a particular focus on the period 2021–2026. The study aims to compare the emigration of Romanian workers towards the European Union with the inflow of foreign workers into Romania and to assess the economic and public policy implications of this dual migration process.

The article contributes to the existing literature by providing an updated analysis based on recent statistical data and by highlighting the emerging contradictions within the Romanian labour market.

2. Labour Migration and Labour Mobility

Labour migration is commonly explained through *push–pull* theories, which highlight differences in wages or income levels, employment opportunities and living standards between countries of origin and destination.

In Romania's case, *push* factors such as relatively low wages across various sectors, limited opportunities for professional advancement and career development, as well as persistent regional disparities, have consistently encouraged emigration over recent years.

At the same time, *pull* factors in destination countries include higher incomes, better working conditions and more stable and flexible labour markets, along with professional opportunities for skilled workers.

Labour mobility also plays an important role in the adjustment mechanisms of labour markets, particularly within the European Union.

The free movement of workers allows individuals to relocate as a natural response to economic imbalances, contributing to economic and social efficiency, while at the same time generating several challenges for countries of origin.

Although labour mobility can reduce pressures related to unemployment, it may also lead to labour shortages, skills mismatches and demographic imbalances between regions and countries.

In the post-pandemic context, labour migration has been influenced not only by economic factors, but also by institutional factors and by public and social policies implemented by national authorities.

The restrictions imposed during the pandemic highlighted the strong dependence of many economies on mobile labour, especially in essential sectors affected by COVID-19, such as HORECA, transport, tourism, the food industry and trade.

For Romania, the resumption of migration flows after 2021 coincided with an increasing reliance on foreign workers, generating a complex and sometimes contradictory dynamic on the labour market, which has created more tensions than flexibility.

3. Methodology and Data Sources

This study is based on a descriptive and comparative analysis of labour migration trends in Romania over the period 2021–2026.

The analysis relies on data obtained from official national and international sources, including Eurostat, the National Institute of Statistics, the General Inspectorate for Immigration, the World Bank and the Organisation for Economic Co-operation and Development.

The article examines both the external migration of Romanian citizens towards the European Union and the inward migration of foreign workers to Romania. Attention is given to the evolution of work permits issued to non-EU workers, with a specific focus on migrants originating from Nepal.

3.1. Romanian Labour Migration to the European Union in the Post-Pandemic Period

Labour migration from Romania to the European Union remains one of the most significant demographic and economic phenomena affecting the country over the past two decades. After a temporary slowdown in migratory flows during the COVID-19 pandemic, labour mobility resumed at an accelerated pace starting in 2021.

Countries such as Italy, Germany, Spain and France continue to be the main destinations for Romanian workers, both skilled and unskilled.

Recent statistical data indicate that the number of Romanian citizens living and working in other EU Member States has remained at a relatively high level, exceeding several million people over the past five years.

Most unskilled Romanian migrants are employed in sectors such as construction, agriculture, healthcare, transport and domestic services.

These sectors frequently face labour shortages in host countries, which makes Romanian workers an essential component of European labour markets, particularly in highly demanded fields of activity.

From an economic perspective, labour emigration has both positive and negative effects on Romania.

Remittances sent back home after 2021 contribute significantly to household incomes and to personal consumption (Cp), while emigration also reduces unemployment pressures in certain regions of the country.

However, the long-term economic effects include labour shortages, losses of professional skills and an accelerated ageing of the population.

These developments raise serious concerns for Romania in the coming years, especially in terms of ensuring sustainable economic development over the medium and long term.

3.2. A Growing Trend of Foreign Immigrants in Post-Pandemic Romania

Alongside the emigration of Romanian workers, Romania has recorded a significant increase in the number of foreign workers over the past five years.

After 2021, Romanian employers across various sectors increasingly turned to labour from outside the European Union to cover existing labour shortages on the domestic market.

Among the main countries of origin of these workers are Nepal, Sri Lanka, India and Bangladesh.

Data provided by the General Inspectorate for Immigration show a steady increase in the number of work permits granted to non-EU citizens over the last five years. Workers from Nepal and Sri Lanka represent some of the largest immigrant groups, being mainly employed in sectors such as construction, manufacturing, HoReCa, transport and agriculture.

These sectors face an acute shortage of domestic labour, particularly for jobs involving physically demanding tasks or more difficult working conditions, often offered at the minimum wage level.

From an economic perspective, the use of foreign workers has become a short-term solution for maintaining business activity in these sectors.

However, this migratory phenomenon also raises several long-term challenges related to social integration, contractual stability, language barriers and the protection of labour rights in Romania.

In the absence of coherent integration policies, the risk of social and economic imbalances remains high, generating further challenges that Romanian public institutions will need to address and manage appropriately.

Year of arrival in Romania	Total number of foreign workers
31 December 2020	25. 635 persons
31 December 2021	33.666 persons
31 December 2022	51.580 persons
31 December 2023	74.398 persons
31 December 2024	100.298 persons
31 May 2025	119.668 persons

Table no. 1. Evolution of the number of foreign workers holding work permits in Romania[3]

The data presented in Table no. 1 show an accelerated and constant increase in the number of foreign workers holding work permits in Romania between 2020 and 2025.

Compared to 2020, when their number stood at 25,635 persons, by May 2025 it reached 119,668 persons, representing an almost fivefold increase within just five years.

This evolution points to a significant and dynamic shift in the Romanian labour market, driven primarily by the shortage of domestic labour.

The most pronounced growth is observed in the post-pandemic period, starting in 2022, when the Romanian economy entered a phase of recovery and labour demand rose rapidly across several economic sectors.

The growth rate recorded between 2022 and 2024 indicates that hiring foreign workers has become an important solution for Romanian employers seeking to maintain business operations, profitability and turnover.

In this macroeconomic context, the import of foreign labour has been used to support economic activity, especially in sectors characterised by difficult working conditions,

[3] General Inspectorate for Immigration https://igi.mai.gov.ro/statistici/.

limited opportunities for professional advancement and relatively low wage levels, with most foreign workers being employed at the statutory minimum wage.

In the absence of effective policies aimed at reducing the emigration of domestic labour, employers were forced to turn to foreign workers to avoid operational and production bottlenecks, meet market demand and sustain business profitability.

In the medium and long term, this growing reliance on imported labour may have significant implications for labour costs, productivity and social cohesion, particularly in the absence of clear strategies for integration and human capital development across different sectors of activity.

Overall, labour migration has become a key factor shaping the functioning of the Romanian labour market in the post-pandemic period.

3.3. Comparative Analysis: Romanian Emigrants and Foreign Immigrants in Romania

In the post-pandemic period, Romania's labour market has been characterised by a paradoxical dynamic. On the one hand, millions of Romanian citizens are working in other European Union Member States such as Italy, Spain, France, Germany and the United Kingdom.

On the other hand, the Romanian economy has become increasingly dependent on foreign labour to sustain domestic economic activity in sectors where Romanian workers are unwilling to accept jobs paid at the minimum wage level.

This situation highlights the presence of deep structural imbalances over the medium and long term, affecting the financial performance of firms operating in these sectors and increasing their dependence on foreign labour.

Wage differentials, working conditions and opportunities for professional development continue to stimulate the long-term emigration of Romanians, while local employers face serious difficulties in recruiting qualified personnel, often being forced to hire unskilled foreign workers.

As a result, the import of foreign labour represents a compensatory solution, but not a sustainable one in the long run.

By comparison, Romanians working in EU countries generally benefit from higher incomes and more comprehensive social protection, whereas foreign workers in Romania often occupy low-skilled positions and face a higher degree of professional and social vulnerability on the labour market.

This imbalance significantly intensifies challenges related to social and economic cohesion, as well as the overall efficiency of the labour market in the short, medium and long term.

The data presented in Table no. 2 illustrate the geographical structure of non-EU labour in Romania in 2025 and show a strong concentration of foreign workers originating from Asian countries, most of them economically disadvantaged.

Nepal ranks first, with 39,723 persons, accounting for approximately one third of all officially registered non-EU workers in Romania.

This high share indicates that recruitment from Nepal has become an important source of labour for Romanian employers, particularly in sectors facing acute shortages of domestic workers.

Sri Lanka and India follow, with 20,704 and 10,906 persons respectively, reinforcing the trend of directing migratory flows towards South and Southeast Asia.

The presence of these workers reflects both the availability of labour in the countries of origin and the relatively lower costs associated with recruitment processes.

At the same time, it suggests the existence of already established migration networks that facilitate labour mobility from these predominantly poor Asian countries to Romania.

The data in Table no. 2 also show that countries such as Turkey, Bangladesh, Egypt, Pakistan, Vietnam and the Philippines contribute to a smaller but relatively stable share of the total number of non-EU workers.

The diversity of countries of origin points to an expansion of foreign labour recruitment processes and to a growing dependence of the Romanian labour market on external sources of labour.

In this context, Romania appears to be aligning with a model observed in other European economies in transition, which increasingly rely on immigration to compensate for demographic decline and occupational shortages across various sectors of the economy.

In the post-pandemic period, the Romanian labour market has been shaped by a rather paradoxical dynamic.

On the one hand, millions of Romanian citizens are working in other Member States of the European Union, such as Italy, Spain, France, Germany and the United Kingdom.

On the other hand, the Romanian economy has become increasingly dependent on foreign labour to sustain domestic economic activity in sectors where Romanian workers are unwilling to accept jobs paid at the statutory minimum wage.

This situation highlights the existence of deep structural imbalances in the medium and long term, affecting the financial performance of firms operating in these sectors and increasing their dependence on foreign labour.

Wage differentials, working conditions and opportunities for professional development continue to encourage the long-term emigration of Romanian workers, while local employers face major difficulties in recruiting qualified personnel, often being forced to hire unskilled foreign workers.

As a result, the import of foreign labour represents a compensatory solution, but not a sustainable one in the long run, either for firms or for employers.

By comparison, Romanians working in EU countries generally benefit from higher incomes and much stronger social protection, while foreign workers in Romania often occupy low-skilled positions and face a higher degree of professional and social vulnerability on the labour market.

This imbalance significantly intensifies challenges related to social and economic cohesion, as well as the overall efficiency of the labour market in the short, medium and long term.

The data presented in Table no. 2 highlight the geographical structure of the non-EU labour force in Romania in 2025 and show a strong concentration of foreign workers originating from Asian countries, most of them economically disadvantaged.

Nepal ranks first, with 39,723 persons, accounting for approximately one third of the total number of non-EU workers officially registered in Romania.

This high share suggests that recruitment from Nepal has become an important source of labour for Romanian employers, especially in sectors facing severe shortages of domestic workers.

Sri Lanka and India follow, with 20,704 and 10,906 persons respectively, reinforcing the tendency of migration flows to be directed towards South and Southeast Asia.

The presence of these workers reflects both the availability of labour in the countries of origin and the relatively lower costs associated with recruitment processes.

At the same time, it points to the existence of already established migration networks that facilitate labour mobility from these predominantly poorer Asian countries to Romania.

The data in Table no. 2 also show that countries such as Turkey, Bangladesh, Egypt, Pakistan, Vietnam and the Philippines contribute to a smaller, yet relatively stable, share of the total number of non-EU workers.

The diversity of countries of origin indicates an expansion of foreign labour recruitment processes, as well as a growing dependence of the Romanian labour market on external sources of labour.

In this context, Romania appears to be aligning with a model observed in other European economies in transition, which increasingly rely on immigration to compensate for demographic decline and occupational shortages across various sectors of the economy.

Country of origin of foreign immigrants in Romania (2025)	**Total number of persons**
Nepal	39 723
Sri Lanka	20 704
India	10.906
Turcia	7610
Bangladesh	7506
Egipt	3422

Pakistan	3387
Vietnam	3174
Filipine	2877
Republica Moldova	2803
Total persons	**119,668 officially registered persons in Romania with valid work permits**

Table no. 2. Countries of origin of non-EU workers in Romania in 2025[4]

An important aspect worth mentioning is the presence of the Republic of Moldova among the main countries of origin, with 2,803 persons.

Although this number is significantly lower compared to Asian countries, this category has a particular importance due to cultural and linguistic proximity, which makes the integration of Moldovan citizens into the Romanian labour market considerably easier.

The structure by countries of origin of non-EU workers reflects a profound change in the functioning mechanisms of the Romanian labour market in the medium and long term.

The rapid increase in workers from Asia highlights both the limits of policies aimed at retaining the domestic labour force and the clear need for more coherent strategies of economic and social integration of foreign workers in Romania.

In the absence of such measures implemented by the Romanian state in the medium and long term, the risk of emerging social, political and economic vulnerabilities remains relatively high in the coming years.

The distribution of Romanians across the main destination countries indicates a relatively dispersed migration pattern yet clearly concentrated in major economies of the European Union.

This homogeneous structure suggests a labour mobility primarily oriented towards stable employment opportunities, secure incomes and developed labour markets that tend to be less volatile and more balanced in the medium and long term.

In contrast to migration flows towards non-EU countries, where temporary workers and low-skilled labour tend to dominate (a feature particularly characteristic of Asian workers coming to Romania), Romanian migration to the European Union shows a more diverse structure.

[4] Inspectoratul General pentru Imigrari https://commission.europa.eu/strategy-and-policy/priorities-2020-2025/promoting-our-european-way- life/statistics-migration-europe

It includes both highly skilled labour (such as IT, engineering, architecture, medicine and education) and low-skilled labour (domestic activities, food industry, construction, agriculture and HORECA).

The data presented allow for a direct comparison between two complementary processes: the emigration of Romanians to EU Member States, analysed in terms of structure and destinations, and the immigration of foreign labour into Romania, analysed by countries of origin.

This comparative perspective highlights the existence of a bidirectional, structurally embedded migration process across different sectors of activity.

It goes far beyond a temporary post-pandemic phenomenon and reflects a deep and complex economic and social process, with both positive and negative effects on a continuously changing labour market, as well as on demographic dynamics and public policies implemented by the state.

Destination country of Romanian emigration	**Total number of Romanian residents in 2024**
Italia	1.070.000 persons
Germania	776.000 persons
Spania	620.000 persons
Other European Union countries (France, Belgium, Netherlands, Austria)	643.000 persons

Tabelul nr.3. Principalele țări de destinație ale românilor în anul 2024 din Uniunea Europeana[5]

Table no. 3 clearly shows that Romania has one of the largest active diasporas of emigrants within the European Union. According to data provided by Eurostat for 2024, approximately 3.1 million Romanian citizens live in other EU Member States, placing Romania first in the European Union in terms of the absolute number of emigrants residing in other community countries. In this context, Romanians represent one of the most significant foreign diasporas within the EU.

Italy represents the largest Romanian community in the diaspora, with around 1,070,000 persons, meaning more than one third of all Romanians residing in another EU country. This situation reflects a long-standing migration tradition towards Italy, reinforced over time by the existence of a stable and heterogeneous Romanian community.

[5] Eurostat: Demography of Europe – 2025 https://ec.europa.eu/eurostat/databrowser/bookmark/a2e95b51-c08a-462c-b4b7-c0a11bab32a7?lang=enidem

Family networks, together with employment opportunities across various sectors of the Italian economy, have played an important role in maintaining this migration flow.

Germany is the second most popular destination country for Romanian migrants, hosting almost 776,000 Romanian residents, while Spain ranks third, with approximately 620,000 persons.

These aggregated indicators for 2024 confirm the strong orientation of Romanian emigrants towards large European economies, characterised by relatively strong and stable labour markets and a sustained demand for labour across multiple sectors of activity.

The remaining Romanian communities in other EU Member States (including the Netherlands, Austria, Belgium, France and other countries) are jointly estimated at over 600,000 persons, completing the total of around 3.1 million Romanian emigrants residing in the European Union.

Overall, Romanians account for approximately 3.1 million people, representing about 22% of all EU citizens living and working in a Member State other than their country of origin. According to Eurostat data recorded on 1 January 2024, they constitute the largest officially registered group of EU citizens residing abroad within the Union.

3.4. Remittances as an Economic Link between Emigration and Immigration

From a macroeconomic perspective, remittances are mainly reflected in GDP through final household consumption (Cp), rather than through productive investment.

One of the most representative methods by which remittances are highlighted in GDP is the expenditure method, which is given by the formula: $GDP = C + I + G + (X - M)$.

Gross Domestic Product (GDP) can be expressed as the sum of household consumption (C), investment (I), government expenditure (G), and net exports (X − M).

For Romania, household consumption represents the primary channel through which remittances generated by labour migration affect overall economic activity.

As shown in *Table no. 4*, remittances sent by Romanian workers abroad accounted for a non-negligible share of GDP during the 2020–2025 period, mainly due to their strong impact on personal consumption.

Income earned abroad is predominantly used for current household expenditures such as goods and services, utilities, education and housing-related costs—thus directly supporting aggregate demand.

While investment reflects expenditures aimed at expanding productive capacity and government expenditure covers public spending on essential services and infrastructure, net exports capture the balance between exports and imports and indicate the degree of external dependence of the economy.

In this context, remittances contribute indirectly to GDP growth by sustaining household consumption, while also highlighting persistent structural imbalances on the domestic labour marke

Year	Remittances sent to Romania by Romanians abroad (EUR billion)	Contribution of remittances to Romania's GDP through personal consumption (Cp, %)	Remittances sent home by foreign workers in Romania (EUR billion)
2020	(lower estimated values)	-	0,394
2021	~8,2 (≈ 9,523 mil USD)	~3,2%	-
2022	high value (close to 2021)	-	-
2023	~6,5	~2,0%	-
2024	~6,7	~2,0%	1,369
2025	~12 (2025 estimate)	~3,1%	-

Table no. 4. Evolution of remittances sent to Romania in the period 2020–2025[6]

3.5. Public Policies and Institutional Responses

Romanian authorities have attempted to respond to labour shortages by increasing the annual quotas for foreign workers admitted to the labour market, particularly in sectors such as tourism, HORECA, transport, telecommunications, and the public and food industries.

At the same time, several administrative measures have been introduced to simplify the procedures for obtaining work permits for foreign workers.

However, existing domestic policies remain largely oriented toward short-term solutions rather than long-term structural approaches.

The lack of coherent strategies aimed at retaining the domestic workforce, insufficient investment in vocational training, and persistent regional disparities continue to limit the effectiveness of current social and labour market policies.

In addition, integration programmes for foreign workers are still underdeveloped, which negatively affects employment stability and overall labour productivity.

Under the current circumstances, a more integrated approach is needed—one that connects migration policies with education, employment, and regional development strategies.

Only through such a coordinated framework can a more balanced functioning of the labour market be ensured in the medium and long term.

The article highlights the fact that Romania is going through a transitional phase on the labour market, characterised by high labour mobility and an increasing dependence on migration.

[6] Eurostat: Demography of Europe – 2025 https://www.consilium.europa.eu/ro/policies/ipcr-response-to-crises/

The COVID-19 pandemic accelerated trends that were already present, further amplifying the structural vulnerabilities of the Romanian economy.

Labour migration should not be viewed exclusively as either a negative or a positive phenomenon.

While emigration contributes to higher income levels through remittances, it also generates significant economic and social costs.

Similarly, labour immigration can support economic activity, but it requires adequate integration and regulatory policies, implemented by state institutions over the medium and long term.

3.6. Digitalisation of the Labour Market in the Context of Labour Migration

In recent years, labour migration in Romania has increasingly become a data-dependent phenomenon, which has required, in the last years, the use of advanced digital tools and information systems for monitoring, forecasting and supporting public policies related to the migration process.
At both European Union level and national level, the digitalisation of labour markets has led to the development and implementation of integrated information systems, having as a main objective the monitoring of migration flows, work permits, labour shortages, as well as the available workforce in different fields of activity, determined by the division of labour, and the registered labour demand in real time.

In Romania, data regarding labour migration are currently dispersed among several public institutions at county level, such as national and local statistical institutes, official immigration authorities and labour employment agencies operating in each county. The lack of a performant and integrated digital system for managing labour migration significantly limits the functional capacity of public institutions, especially in terms of anticipating the current labour shortages in Romania and designing public policies based on solid and conclusive evidence.

In this context, the use of information technologies based on Big Data and machine learning models integrated into information systems could considerably improve the monitoring of the migration process, as well as the development of realistic forecasts regarding future labour migration trends in Romania for the coming years.
The application of predictive analyses on migration data would allow the identification of economic sectors that are more exposed to labour shortages, as a result of estimating the future demand for foreign workers (foreign immigrants), and the evaluation of the impact of emigration on domestic employment in different branches and sectors of the economy.

These predictive models and analyses can be developed and processed using extended datasets that combine various administrative information, labour market statistics and macroeconomic indicators, offering more accurate and faster results compared to the traditional descriptive approaches currently used by public institutions responsible for collecting such data.

At the same time, the digitalisation of the labour market has significantly transformed, in recent years, recruitment processes and human resource management. Automated recruitment platforms already used by employers, HR analytics tools and algorithm-based systems for matching candidates' professional skills are increasingly applied at European level for identifying candidates, managing labour mobility and optimising human resource allocation.

In Romania, these information technologies for candidate selection can contribute to a significant increase in the efficiency of recruitment processes, applied both to domestic and foreign workers, while at the same time reducing the informational asymmetries currently existing on the labour market, generated by structural unemployment and the division of labour.

The integration of digital tools and information systems, as well as data-based models, into the management of labour migration represents a new and necessary stage for ensuring a labour market that is more efficient, transparent and resilient to economic, political and social changes in the medium and long term.
For Romania, progress in this direction, through digitalisation and the implementation of a performant information system, would strengthen institutional capacity in the long run and would allow the alignment of social and public policies regarding labour migration with the broader European Union objectives of digital transformation, promoted at European level, in the current context of globalisation and labour mobility.

4. Conclusions

In the post-pandemic period, Romania is facing a complex configuration of its labour market, marked by persistent emigration and a significant increase in the number of foreign workers over the past five years.

This dynamic reflects deep structural imbalances that cannot be corrected solely through administrative or short-term policy measures.

The results of the analysis suggest that, in the absence of coherent and integrated public policies, Romania's dependence on foreign labour will continue to increase, while the emigration of Romanian workers is likely to remain high in the coming years.

To ensure sustainable economic development, a long-term strategy is required, focused on improving working conditions, increasing labour productivity across different sectors, and encouraging the return of the domestic workforce.

Another important aspect highlighted in the article concerns the nature of labour mobility in Romania.

While Romanian workers continue to migrate to European Union member states in search of higher incomes and more stable working conditions, foreign workers arriving in Romania generally occupy low-skilled positions in sectors characterised by labour shortages and minimum-wage employment.

This difference in professional status and economic opportunities contributes to the persistence of medium- and long-term imbalances on the labour market.

At the same time, it limits the Romanian economy's capacity to attract and retain highly skilled labour across various fields of activity.

Within this macroeconomic context, public and social policies should move beyond a strictly quantitative approach to labour migration and place greater emphasis on the quality of employment and labour market integration.

Investments in training and professional reconversion, recognition of professional qualifications, and improvements in working conditions could help reduce migratory pressures and create a more balanced framework for labour mobility in the years ahead. Such a socio-economic approach would support medium and long-term economic competitiveness and social cohesion, especially in the context of the accelerated transformations currently affecting Romania's labour market in the post-pandemic period.

The analysis of remittances sent by the Romanian diaspora highlights their role as a stable source of income for the Romanian economy in the post-pandemic period.

Available data for the 2020–2025 interval show that the amounts transferred from abroad have remained high, despite global economic uncertainties.

Indirectly, remittances contribute to maintaining living standards and stabilising domestic demand, particularly by supporting household-level consumption at the macroeconomic level.

REFERENCES

[1] European Commission – *Labour mobility in the European Union after COVID-19*. European Commission Report. Brussels. 2022.

[2] Eurostat – *Migration and migrant population statistics*. Eurostat Database. Brussels. 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php/Migration_and_migrant_population_statistics Date of last access: 08-03-2026.

[3] Eurostat – *Population by citizenship and country of birth*. Eurostat Database. Brussels. 2024. https://ec.europa.eu/eurostat/web/population-demography.

Date of la st access: 08-03-2026.

[4] Eurostat – *Demography of Europe – 2025*. Interactive publication. Brussels. 2025. https://ec.europa.eu/eurostat/web/population-demography.

Date of last access: 10-03-2026.

[5] Inspectoratul General pentru Imigrări – *Statistical data on foreign workers in Romania*. Ministry of Internal Affairs. Bucharest. 2025.
Date of last access: 08-03-2026.

[6] International Labour Organization (ILO) – *Global Labour Migration Trends after the COVID-19 Pandemic*. ILO Report. Geneva. 2022.

[7] Organisation for Economic Co-operation and Development (OECD) – *International Migration Outlook 2025*. OECD Publishing. Paris. 2025.
https://www.oecd.org/migration/international-migration-outlook/.

Date of last access: 08-03-2026.

[8] World Bank Group – *Romania: Systematic Country Diagnostic*. World Bank Publications. Washington DC. 2023.

[9] World Economic Forum – *The Future of Jobs Report 2023*. Geneva. 2023.

[10] AGERPRES – *Românii din diaspora au trimis acasă circa 60 de miliarde de euro în perioada 2013–2025 – date BNR.* 2025. Date of last access: 15-03-2026.

[11] European Commission – *Labour Market Information Systems and Digitalisation*. Brussels. 2022. https://commission.europa.eu/employment-social-affairs/labour-market-information-systems_e. Date of last access: 16-04-2026.

[12] International Labour Organization (ILO) – *Digital Labour Platforms and the Future of Work*. Geneva. 2021. https://www.ilo.org/global/topics/future-of-work/digital-labour-platforms/lang--en/index.htm. Date of last access: 16-04-2026.

[13] Curs de Guvernare – *Banii trimiși acasă de lucrătorii străini din România au depășit 1,3 miliarde euro în 2024*. https://cursdeguvernare.ro/banii-trimisi-acasa-de-lucratori-straini-din-romania-au-depasit-13-mld-euro-in-2024. Date of last access: 17-03-2026.

[14] Ziarul Financiar – *Remiterile totale ale lucrătorilor străini au ajuns la 1,7 miliarde euro*. 2025. Date of last access: 23-03-2026.

[15] Romania Insider – *Romanians working abroad sent EUR 60 billion back home over the past 12 years*. 2025. Date of last access: 20-03-2026.

BIBLIOGRAPHY

ARNTZ, M.; GREGORY, T.; ZIERAHN, U. – *The Risk of Automation for Jobs in OECD Countries*. OECD Publishing. Paris. 2016.

ARSENE, Andreea - *Travellers into the Giant Space of Globalization – Migration Phenomenon and its Implications at the Family Level* - Revista de Administraţie Publică şi Politici Sociale Anul I, Nr. 2 / Martie 2010- Paper accessed on 25.03.2026.

BORJAS, G. J. – *Labor Economics*. McGraw-Hill Education. New York. 2019.

BOSWELL Christina - *Addressing the causes of migratory and refugee movements: the role of the European Union* – December 2002

CHRISTL,M.; A. BÉLANGER, A. CONTE, J. MAZZA, E. NARAZANI - *Projecting the fiscal impact of immigration in the European Union, Fiscal Studies* The Journal of Applied Public Economics, Volume 44, Issue 3 (2021), https://wileyonlinelibrary.com/journal/fisc, paper accessed on 25.03.2026

EUROPEAN COMMISSION – *Digital Education Action Plan 2021–2027*. Brussels. 2021.

EUROPEAN COMMISSION – *Labour Mobility and Skills Shortages in the European Union*. Brussels. 2023.

INTERNATIONAL LABOUR ORGANIZATION (ILO) – *World Employment and Social Outlook: Trends 2023*. Geneva. 2023.

PESCARU, C. M. - *International migration and European integration – factor of globalization [Migratia internationala si integrarea europeana-factor al globalizarii].* In Rogojanu, D. C. (coord.) (2014). Regionalizare si politici regionale, pp.187-196. Iasi, Romania: Editura Lumen. Paper accessed on 24.03.2026

KEYNES, J. M. – *The General Theory of Employment, Interest and Money*. Macmillan. London. 1936.

OECD – *The Digital Transformation of Education: Connecting Schools, Empowering Learners*. OECD Publishing. Paris. 2021.

OECD – *International Migration Outlook*. OECD Publishing. Paris. 2023.

SCHWAB, K. – *The Fourth Industrial Revolution*. World Economic Forum. Geneva. 2016.

SUSSMUTH, Rita. WEIDENFELD. Werner - *Challenge integration: Living together in a Europe of diversity* - 2004.

NOVARA. C., M.J. MARTOS-M´ENDEZ , L. GOMEZ-JACINTO, I. HOMBRADOS-MENDIETA , L. VARVERI, C. Polizzi - *The influence of social support on the wellbeing of immigrants residing in Italy: Sources and functions as predictive factors for life satisfaction levels, sense of community and resilience*, International Journal of Intercultural Relations 92 (2023) 101743, http://www.elsevier.com/locate/ijintrel

WORLD BANK GROUP – *Digital Transformation in Romania: Country Diagnostic*. World Bank Publications. Washington DC. 2022.

https://ec.europa.eu/eurostat/ark/ -link accessed on 19.03.2024.

https://www.consilium.europa.eu/ro/policies/ipcr-response-to-crises/ - link accessed on 19.03.2026.

https://ec.europa.eu/eurostat/ - link accessed on 20.03.2026.

https://www.unhcr.org/refugee-statistics/ - link accessed on 20.03.2026.

https://commission.europa.eu/strategy-and-policy/priorities-2010-2025/promoting-our-european-way- life/statistics-migration-europe - link accessed on 20.03.2026.

ANALYSIS OF THE STUDENT DEFICIT IN TOURISM SPECIALIZATIONS IN ROMANIA

Gina Gilet (LEFTER) DOBROTĂ[1]

Emilia GABROVEANU[2]

Abstract:

The pandemic was a turning point in changing many consumer habits. Many activities that were prosperous until 2019-2020 declined after this period. From this perspective, it can also be said that online educational services, synchronous or asynchronous, have also changed the consumption habits of young people. Digitalization, new technologies, and artificial intelligence have generated major changes in the mentality of young people. Attention deficit, lack of motivation, patience, or concentration are just a few consequences of using digital communication means. Added to all of this were, on one hand, the attractive educational offers of European universities, but also the low salaries in certain fields. In this context, Romanian universities are facing a student deficit. Year after year, the number of students decreases, not only in specializations that are no longer found in labor market demands but also in programs dedicated to fields with an acute need for workforce. The causes are multiple, including the lack of desire among high school graduates to continue their studies and the choice of other countries to pursue university studies, among others. Starting from these premises, the present study aims to identify, through a quantitative and qualitative analysis, the causes of the student deficit in faculties specializing in tourism in Romania.

Keywords: Higher Education, Economics Education Research, Tourism, Technological Change, Digitalization of education

JEL Classification: A290, J490, I210, I230, Z310, Z320, I25, O39, O00.

1. Market Analysis of Higher Education in Tourism in Romania

The declining student enrollment trend observed across European higher education institutions—a phenomenon not restricted to the Romanian context—has been well-documented over the past several years and continues to escalate. The etiology of this deficit is multifaceted, requiring universities to undergo strategic realignment and institutional reinvention. To remain competitive, institutions must transition toward proactive recruitment frameworks targeting secondary education graduates. Notably, educational

[1] PhD , Lccturer, Romanian-American University, Bucharest, Romania, email:gina.gilet.dobrota@rau.ro
[2] PhD Assistant professor, Romanian-American University, Bucharest, Romania, email: emilia.gabroveanu@rau.ro

models in jurisdictions such as the Netherlands, the United Kingdom, and Germany prioritize continuous curricular updates, holistic student development, and the integration of state-of-the-art technologies as primary mechanisms for institutional adaptation.

According to data provided by the Ministry of Education, the number of high school graduates in 2025 experienced a 20% decline compared to 2024. Furthermore, over 62,500 students who enrolled in the primary education system in 2012 were no longer accounted for by the time of the 2025 baccalaureate examination; consequently, over the course of 13 years of schooling, nearly four out of ten students either dropped out or failed to sit for the final examination.

In addition to these systemic leaks, a significant proportion of youth opt for immediate entry into the labor market following secondary education [5]. Others, supported by parental resources, defer their higher education by taking a 'gap year' for travel or to undergo intensive preparation for admission into vocational and specialized institutions.

Eurostat data further confirm that Romania records the lowest rate of tertiary education attainment within the European Union. In 2022, only 17.4% of the Romanian population aged 25 to 74 held a higher education degree, significantly below the European average of 32%. The majority of the population - exceeding 60% - possesses only secondary education, while approximately 22% have not completed high school studies.

Furthermore, according to 'The Situation of Young People in the European Union' report, Romania faces a critical challenge regarding the NEET (Not in Education, Employment, or Training) population. In 2023, Romania registered the highest NEET rate in the EU at 19%, reflecting an upward trend from 16.8% in 2019. Romania stands as the only EU member state where this indicator has deteriorated rather than improved. Consequently, despite the thousands of positions made available by Romanian universities during the autumn admission sessions, youth interest in pursuing higher education is visibly declining[4].

Comparative analysis shows that even countries such as Italy and Hungary, which rank near the bottom of the European scale alongside Romania, maintain a tertiary education attainment rate approximately 10 percentage points higher. Additionally, Bulgaria has reached a rate of 50%, while the overall European average stands at 44.1% (ec.europa.eu)[1].

Within this broader context, to provide a more precise diagnostic of the enrollment deficit in tourism-related specializations, an analysis of Romania's educational offering in this field was conducted.

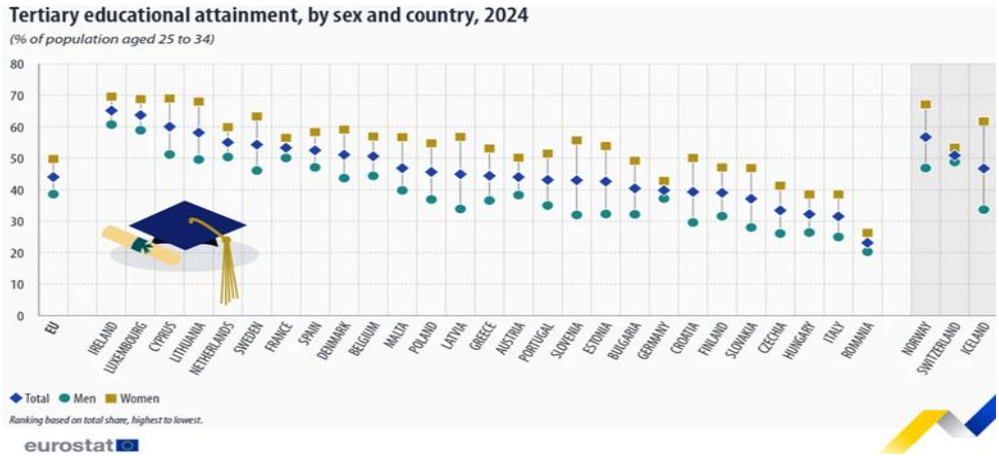


Figure 1. Tertiary educational attainment, by sex and country, 2024[3]

Consequently, theoretical higher education programs in Tourism and Hospitality are available at both undergraduate (Bachelor's) and graduate (Master's) levels across several public and private universities, including:

- The Bucharest University of Economic Studies (ASE) – The Faculty of Business and Tourism, which offers undergraduate degrees in Business Administration in Tourism and Services, alongside Master's and Doctoral programs;
- The University of Bucharest – Which provides 'Tourism Geography' programs, including distance learning and part-time attendance options;
- The Universities of Oradea, Târgoviște, and Constanța – Offering undergraduate programs in Tourism and Hospitality or the Geography of Tourism;
- Transilvania University of Brașov (UNITBV) – Through the Faculty of Food and Tourism, which offers specialized curricula in tourism education and hospitality management;
- The Romanian-American University – The Faculty of Tourism and Hospitality Management, featuring Bachelor's and Master's specializations focused on tourism and management, with an emphasis on practical collaborations with the business environment."

The orientation of these programs varies significantly: while some are predominantly vocationally-oriented, focusing on hospitality management, others emphasize the geographical and sustainable analysis of tourism or the strategic management of tourism resources.

At the European level, hundreds of specialized programs in Tourism & Hospitality Management are offered by universities and business schools. These Bachelor's and Master's programs—available in countries such as Austria, Spain, Poland, Greece, Germany, and Sweden—encompass curricula in hospitality management, international

[3] Source: https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20250904-1

tourism, and destination development [6]. Prestigious institutions, most notably École Hôtelière de Lausanne (Switzerland), continue to lead international rankings in the hospitality sector. Furthermore, specialized schools and international programs offer degrees characterized by a strong emphasis on experiential learning, mandatory internships, and global mobility [7].

A 2023 study conducted by World Vision Romania, in partnership with Babeș-Bolyai University, highlighted a significant disparity between Romania and the European Union average regarding higher education attainment rates. The findings revealed that only 23.3% of Romanian youth enrolled in higher education successfully completed their degrees, a figure substantially lower than the EU average of 41.2% [3]. Furthermore, over 65% of high school graduates from rural areas do not pursue university studies, despite 80% expressing an initial intention to continue their education. Economic constraints remain a decisive factor, as one in three young people identifies the lack of financial resources as the primary barrier to accessing tertiary education.

In a separate study conducted by George Pop (alumnus of the MSc in Tourism Marketing at the University of Surrey and coordinator of the professional tourism blog oradeturism.wordpress.com), an inventory of the public theoretical higher education offering revealed 35 tourism programs across Romania [2]. The analysis of these public institutions indicates a lack of dedicated, standalone faculties of tourism. Instead, tourism education is integrated into multidisciplinary frameworks: coupled with 'Business' at the Bucharest University of Economic Studies; with Geography and Sports at the University of Oradea; with Public Catering at the Transilvania University of Brașov; or alongside Economic Sciences, Business, and Geography at Babeș-Bolyai University in Cluj-Napoca.

Furthermore, while every National Tourism Development Master Plan over the last 30 years has identified spa, cultural, and rural tourism as the primary strategic pillars for development, the national educational offering remains insufficiently aligned. Specifically, there are only a limited number of agritourism programs, such as those at the University of Agronomic Sciences and Veterinary Medicine, within the Faculty of Horticulture, titled 'Engineering and Management in Public Catering and Agritourism' and 'Engineering and Management in the Tourism Industry.' Similar multidisciplinary specializations are found at the University of Agricultural Sciences and Veterinary Medicine in Timișoara, the Faculty of Natural and Agricultural Sciences in Constanța (offering a BA in the Geography of Tourism), and the University of Medicine, Pharmacy, Science and Technology of Târgu Mureș. Consequently, the study identified 15 programs specialized in the 'Economy of Trade, Tourism, and Services' and 9 programs focused on 'Tourism Geography'.

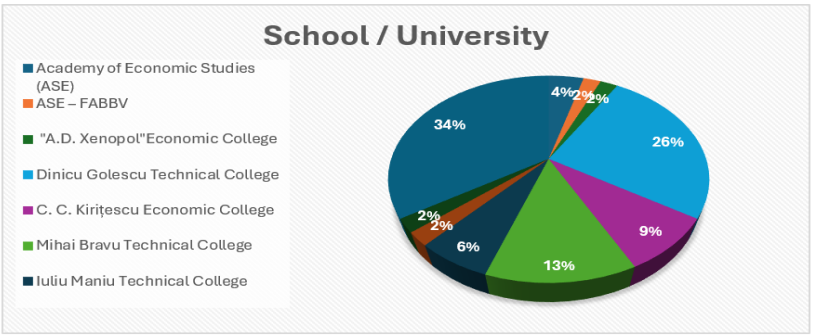
2. Analyzing the lack of interest in higher tourism education among high school students. A quantitative study

Building upon these findings, this study was conceived to investigate the lack of educational continuity between secondary and tertiary levels within the tourism sector. Specifically, the research aims to analyze the factors preventing students from pursuing higher education degrees in the same field of study following their graduation from specialized vocational or theoretical high schools

The study employed a quantitative research design, utilizing a digital questionnaire as the primary instrument for data collection. The survey was disseminated via social media platforms, email, and instant messaging applications to a sample of 64 high school students and recent graduates from vocational and technological tracks specializing in tourism. The primary objective of the questionnaire was to identify the underlying factors that deter graduates with specializations such as 'Tourism Technician' or 'Hotel Management Technician' from pursuing higher education degrees within the same field.

The sample predominantly consisted of young adults (83%) within the 18 to 24 age cohort. Furthermore, the demographic distribution achieved gender parity, covering both sexes in similar proportions.

Regarding the current field of study of the participants, the research objectives were successfully met, as the sample comprised 12th-grade students from five technological and economic high schools (56%), all of which were specialized in tourism. Furthermore, 12% of the respondents are graduates of secondary tourism education currently enrolled at the Bucharest University of Economic Studies, the Romanian-American University, and the University of Agronomic Sciences and Veterinary Medicine; notably, these individuals are pursuing degrees in specializations unrelated to the tourism sector

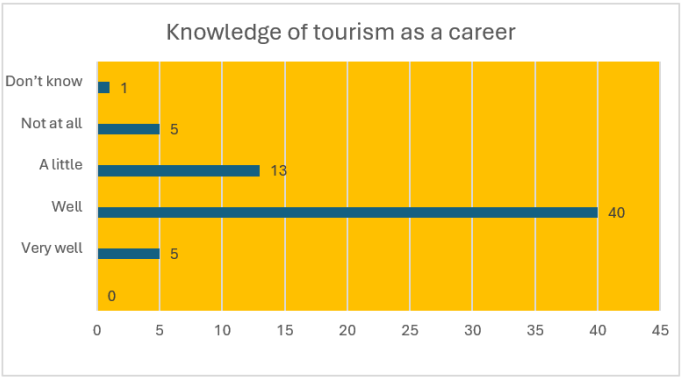


Source: the survey

Figure 2. Educational background of respondents

When queried about their familiarity with tourism as a career path, 62.5% of respondents claimed to know the field 'well,' while a combined 28.12% indicated 'limited knowledge,' 'none at all,' or 'uncertainty.' Within this context, a mere 7.81% reported being 'very well' acquainted with specific career prospects in tourism.

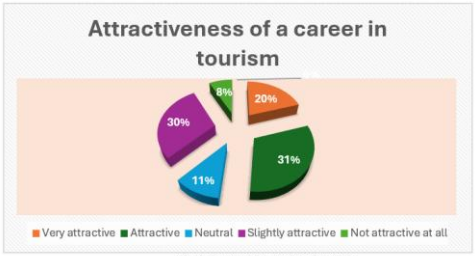
A major discrepancy exists between general awareness of the field and a profound understanding of specific career opportunities. Although a significant majority (62.5%) claim familiarity with tourism as a professional option, the narrow segment of 7.81% possessing 'very good' knowledge suggests a superficial understanding of the labor market. This indicates that while respondents can identify generic roles (e.g., receptionist, tour guide), they lack familiarity with hierarchical career progression or niche specializations within tourism management.



Source: the survey

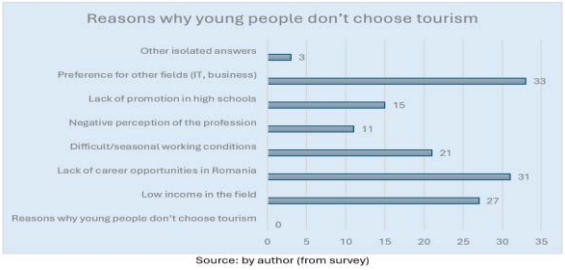
Figure 3. Knowledge of tourism as a career

Despite the fact that approximately 51% of respondents perceive tourism careers in Romania as 'attractive' or 'highly attractive,' with only 18.7% considering them 'low' or 'not at all attractive,' there remains a significant paradox regarding educational continuity. Despite this positive perception of the sector's professional appeal, most respondents do not consider pursuing higher education in tourism to be a viable or preferred career path.



Source: by author (from survey)

Figure 4. Attractiveness of a career in tourism



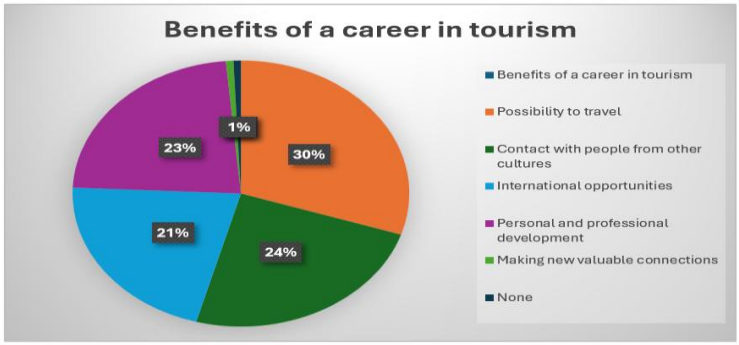
Source: by author (from survey)

Figure 5. Tourism non-selection reasons

The primary obstacle in attracting youth to the tourism sector is a deficit in cross-sectoral competitiveness. Specifically, the preference for alternative fields (n=33) and the perceived lack of career opportunities (n=31) prevail over operational difficulties. This trend indicates a crisis of prestige within the industry and an unfavorable cost-benefit analysis regarding projected income and professional stability.

The most significant inhibitor identified is the competition with alternative industries (such as IT or Medicine), cited by 33 respondents, which underscores a crisis of competitive attractiveness for the tourism sector within the labor market. Furthermore, the perceived lack of career advancement opportunities (n=31) and low income levels (n=27) are identified as major structural obstacles, outweighing the impact of seasonality or the physical/operational difficulty of the work.

The limited impact of institutional promotion within secondary education (n=15) and a general negative perception of the industry (n=11) suggest a systemic deficiency in strategically communicating the sector's benefits to younger generations. The results reveal a striking contrast: while there is a strong collective belief in the capacity of tourism to drive Romania's economic development (62%), youth avoid active engagement in the field due to financial instability and a lack of professional prestige. Paradoxically, while tourism is perceived as a vital pillar for the national economy, it is simultaneously viewed as 'unfriendly' or unattractive from the perspective of individual employment.



Source: by author (from survey)

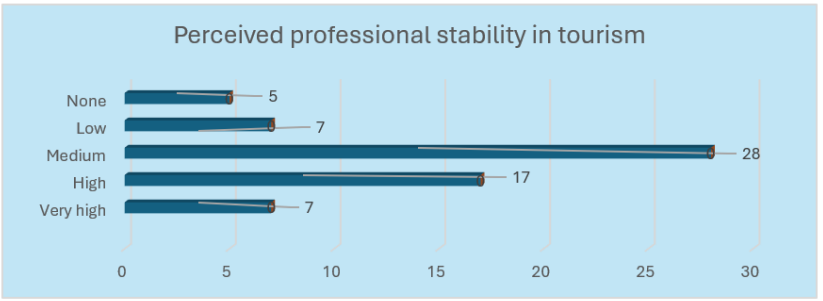
Figure 6. Benefits of a career in tourism

The data regarding the perceived benefits of a career in tourism provide a clear overview of intrinsic motivations: the opportunity to travel represents the primary attractor, cited by 30% of respondents. The intercultural and social dimensions are also strongly represented, with contact with diverse cultures (24%) and international opportunities (21%) being highly valued. Furthermore, 23% of subjects recognize the potential for personal and professional growth, demonstrating that tourism is perceived as a fertile environment for the accumulation of practical experience and 'soft skills.'

However, these findings reveal a structural paradox: although respondents acknowledge the economic significance of tourism (62%) and value its experiential benefits (travel, interculturality), they tend to avoid the sector due to pragmatic deficiencies, such as low wages and career instability. There is a manifest discrepancy between the *ideal value* of tourism—characterized by personal development and national impact—and its *actual market value*, where competition from sectors such as IT is increasingly dominant. To attract younger generations, the industry must translate these intangible benefits (cultural

experiences) into tangible advantages, such as transparent career trajectories and competitive compensation packages.

In conclusion, tourism is perceived predominantly as a domain of life experiences rather than a sector providing long-term financial security or professional stability.



Source: by author (from survey)

Figure 7. Perceived professional stability in tourism

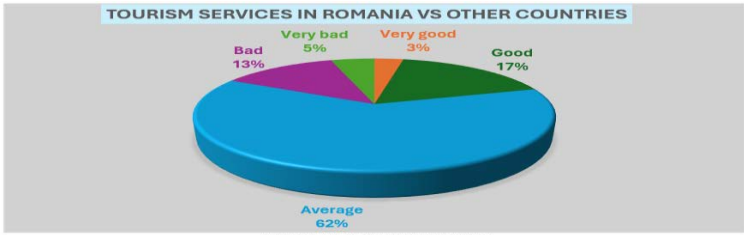
The findings indicate considerable macroeconomic optimism among respondents. A significant majority (62%) believe that tourism can contribute decisively to the country's economic development, while an additional 28% recognize this potential partially. This positive outlook suggests that tourism is perceived as a strategic national asset, even if its benefits are not yet fully leveraged.

Regarding perceived job stability, the data reflect a trend toward neutrality, albeit with visible reservations:

- The largest proportion of respondents (n=28) assess professional stability at a medium level.
- While a segment perceives stability as high (n=17) or very high (n=7), a cumulative total of 12 respondents place the sector in the low or non-existent stability category.

This distribution suggests that tourism is still perceived as a fluctuating field, where long-term career security remains uncertain for a significant portion of the workforce.

The analysis reveals a persistent paradox: although tourism is validated as an economic engine (62%) and offers attractive lifestyle benefits (travel, culture), it fails to provide high perceived stability and competitive income. The gap between *idealized attractiveness* (travel) and *pragmatic reality* (low wages, insufficient promotion) explains why youth migrate toward more secure and better-remunerated sectors.



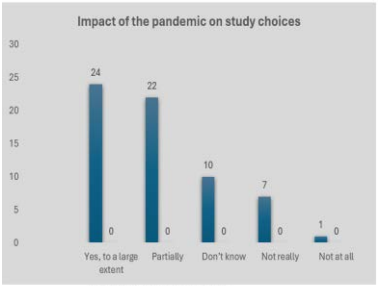
Source: by author (from survey)

Figure 8. Tourism Services in Romania vs Other Countries

An overwhelming majority of 62% of respondents perceive Romanian tourism services as being of 'average' quality compared to international standards. Only 20% evaluate these services as 'good' or 'very good,' while a nearly equivalent proportion (18%) classify them as 'poor' or 'very poor.' Despite this perception of mediocrity in service delivery, 62% of subjects maintain a strong belief in the sector's capacity to contribute significantly to the country's economic development.

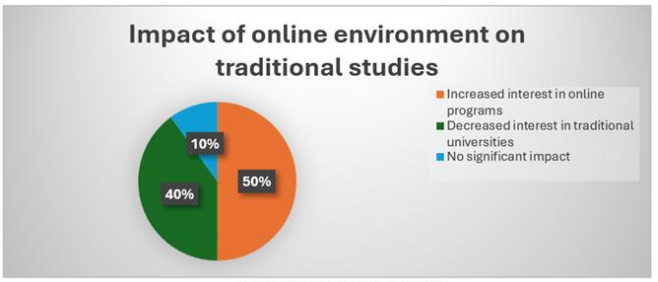
The data concerning the youth demographic elucidate why this aforementioned economic potential remains only partially realized. The analysis reveals a fragile developmental model: Romanian tourism is currently stagnating in a 'median zone' regarding both service quality (62%) and professional stability. Although the public identifies clear benefits related to mobility and interculturality, these factors prove insufficient to offset low wages and the lack of clear advancement prospects.

To transform tourism into a genuine economic engine, a strategic shift is required: transitioning from an attractiveness based on travel perks to an attractiveness rooted in professionalism. This necessitates elevating service quality beyond the current level of mediocrity and restructuring compensation frameworks for young specialists.



Source: by author (from survey)

Figure 9. The pandemic impact



Source: by author (from survey)

Figure 10. The online environment's impact

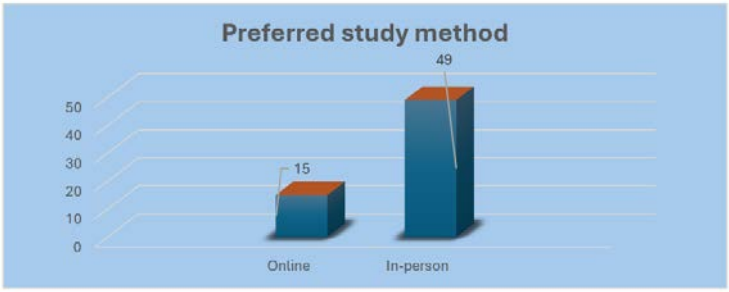
The global health crisis exerted a major disruptive influence on the sector; 24 respondents stated that the pandemic influenced their educational choices 'to a great extent,' while 22 reported a 'partial' impact. The inherent instability of the industry, which was brutally exposed by the pandemic, has solidified the perception of tourism as a high-risk career path. Furthermore, the lack of institutional promotion within secondary education (n=15) leaves

these apprehensions unaddressed, steering youth toward sectors perceived as 'crisis-proof.' Collectively, the data explain the refusal of young people to enter the system through the lens of external competition and the lingering trauma caused by the health crisis.

The digital environment has radically transformed traditional education: 50% of the subjects report an increased interest in online programs, while 40% experience a diminishing interest in classical universities. These findings reflect a massive shift in educational behavior under the dual pressures of digitalization and the global health crisis.

The analysis reveals a fragile developmental model: Romanian tourism suffers from a discrepancy between its image as an economic engine and the pragmatic reality of the labor market. Services remain stagnant in a 'median zone' of quality, stability is perceived as uncertain, and the pandemic has functioned as a catalyst for the migration of educational interest toward online platforms and alternative professional fields.

To revitalize the sector, a transition is required from attractiveness based on experiential factors (travel) to an attractiveness rooted in professionalism. This objective must be pursued by elevating service quality and restructuring academic offerings to regain the trust of the post-pandemic generation.



Source: by author (from survey)

Figure 11. Preferred study method

The survey results highlight a major paradox between the theoretical interest in digitalization and the practical preference for human interaction:

While 50% of respondents express an increased interest in online programs, 40% experience a diminishing interest in traditional universities. This suggests an erosion of the classical academic model in favor of digital flexibility. Only a minor segment (10%) believes that digitalization has had no significant impact on their perception.

Despite this theoretical openness toward the digital medium, when selecting an actual learning modality, an overwhelming majority of 49 respondents prefer the 'face-to-face' method. In contrast, only 15 respondents opted for exclusively online study.

Consequently, while respondents value the online environment for its accessibility and convenience, they continue to associate 'face-to-face' learning with educational quality and the intrinsic value of human interaction. In tourism—a field fundamentally based on

interpersonal relationships—the significant preference for physical attendance (49 out of 64 participants) reflects an understanding that practical skills cannot be fully acquired in a virtual environment.

Although the pandemic forced a migration toward online platforms, influencing the educational choices of most subjects, it has not succeeded in replacing the desire for direct contact. The loss of interest in traditional universities (40%) may not stem from the physical format itself, but rather from a lack of curricular adaptation, given that students still express a desire for in-person learning.

Furthermore, since salary is 'very important' for 39 of the respondents, the preference for 'face-to-face' study can be interpreted as an investment in a form of education perceived as more rigorous and better equipped to ensure the high income they seek.

In conclusion, the Romanian tourism student emerges as a 'hybrid' profile: they demand the flexibility of online resources but base their actual professional development on physical presence, viewing it as the only method capable of providing the competencies necessary for a stable career.

Source: by author (from survey)

Figure 12. Salary as a choice factor

This data indicates an extremely pronounced pragmatic orientation among respondents, reflecting a direct correlation between financial expectations and educational investment. A majority of 39 respondents consider salary to be a 'very important' factor in the university selection process. An additional 21 respondents classify salary as 'important,' meaning that for 60 out of the 64 participants (over 93%), the financial outlook represents either a decisive or a qualifying criterion.

It is noteworthy that no respondent (0) considered salary to be 'not at all important,' while the 'neutral' and 'slightly important' segments remain marginal (2 respondents each). This distribution elucidates why the tourism sector faces recruitment challenges despite being perceived as attractive. Although youth are drawn to the 'opportunity to travel' (30%), this desire comes into direct conflict with an acute need for financial security. Since salary is 'very important' for the majority, and 'low income' is identified as a primary reason for avoiding the sector, an insurmountable selection barrier emerges.

Respondents 'do not believe in the continuity of higher education in tourism' precisely because their perception is that this field cannot satisfy their primary requirement: a motivating post-graduation salary.

In conclusion, the contemporary student no longer selects a faculty based on passion or curiosity alone, but rather on a Return on Investment (ROI) calculation. If tourism is perceived as a low-income sector, no promotional campaign highlighting the 'beauty of the profession' will be able to offset the need for financial stability expressed by the 39 respondents in the final dataset.

Source: by author (from survey)

Figure 13. Specialization choice criteria

According to the recorded responses, the two most critical criteria are employment opportunities and salary levels, each accounting for 33% of the total. This equal weighting suggests that respondents adopt an instrumental perspective on higher education, perceiving it primarily as a vehicle for labor market integration and financial stability. This finding is consonant with Human Capital Theory, which emphasizes the role of education in maximizing individual economic returns.

Personal passion accounts for 26%, ranking third in the hierarchy of criteria. While significant, this value indicates that intrinsic motivation is subordinate to economic considerations. From a pedagogical perspective, this aspect raises questions regarding the long-term sustainability of academic motivation, particularly in fields perceived as demanding or characterized by uncertain financial returns.

The prestige of the university (10%) exerts a moderate influence, suggesting that institutional reputation is relevant but not decisive. In contrast, recommendations from family or friends (6%) hold a minimal weight, indicating a high degree of individual decision-making autonomy among respondents—a hallmark of modern, individualistic societies.

Tuition fees, at only 1%, have a marginal influence. This value may be interpreted in several ways: either costs do not represent a major constraint for the analyzed sample, or they are perceived as an acceptable compromise in relation to the anticipated future benefits.

Overall, the results suggest a predominantly utilitarian orientation in the selection of university specializations, with significant implications for educational policies and vocational guidance strategies.

In conclusion, the study highlights that the decision regarding the choice of a university specialization is dominated by economic and professional considerations, while vocational and social factors play a secondary role. This trend reflects the adaptation of education to labor market dynamics, but it also underscores the necessity of achieving a balance between economic utility and personal fulfillment within the academic and professional trajectory.

Source: by author (from survey)

Figure 14. Internship opportunities offered

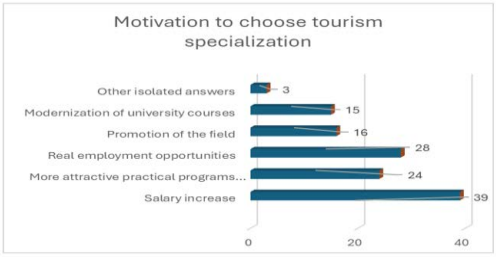
The high prevalence of the 'Partial' response (54%) suggests the existence of internship initiatives; however, these are perceived as insufficient in terms of duration, quality, or relevance to the labor market requirements in the tourism sector. This result reflects a gap between the academic curriculum and the industry's actual needs.

The 'No' response (19%) indicates a significant proportion of respondents who believe that universities do not offer adequate internship opportunities, a factor that may lead to professional integration challenges for graduates. Furthermore, the 'I don't know' category (19%) reveals either a lack of student awareness regarding existing opportunities or a low visibility of partnerships between universities and tourism industry stakeholders.

In contrast, only 8% of respondents believe that universities provide sufficient internship opportunities, highlighting the marginal nature of positive perceptions. These results suggest a critical need for: strengthening partnerships with tourism operators (hotels, travel agencies, destination management organizations); extending the duration and diversifying the forms of practical training (internships, work placements, applied projects); and improving institutional communication regarding available opportunities.

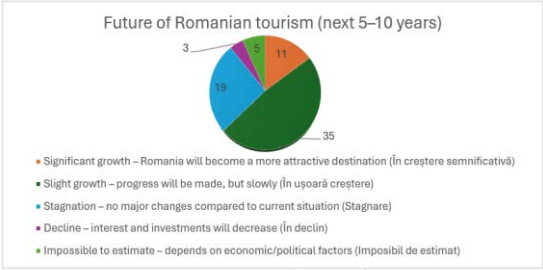
Overall, the data indicate that romanian universities are perceived as offering insufficient or incomplete tourism internship opportunities, which may adversely affect the practical preparedness of graduates. To enhance the quality of academic training, a stronger

orientation toward experiential learning and a closer alignment with labor market demands are essential.



Source: by author (from survey)

Figure 15. Motivation



Source: by author (from survey)

Figure 16. Future of Romanian tourism

The largest share of responses corresponds to the 'slight increase' option (35%), suggesting that respondents perceive Romania's tourism potential as real but insufficiently leveraged. This perception points toward the existence of persistent barriers, such as deficient infrastructure, limited international promotion, or a lack of coherent investment strategies.

Responses indicating stagnation (19%) reflect a significant lack of confidence in the sector's capacity to generate relevant structural changes. This segment of the sample perceives Romanian tourism as relatively inert, dependent on external factors rather than proactive public policies.

Only 11% of respondents anticipate a significant growth, suggesting that strong optimism remains limited. This relatively low value may indicate a perceived absence of clear reform signals or long-term strategic investments. Conversely, the 'decline' option (3%) represents a marginal share, indicating that profoundly negative perceptions are isolated and do not define the general consensus.

The 'impossible to estimate' category (5%) underscores the influence of exogenous factors (economic, political, and geopolitical) and the degree of uncertainty associated with planning within the tourism industry. Overall, 46% of respondents (slight increase + significant increase) anticipate a positive evolution, while 22% (stagnation + decline) express a negative or neutral perception. This balance indicates a state of moderate optimism, yet one that lacks firm conviction.

Consequently, these findings necessitate several strategic actions, such as: the implementation of coherent national strategies for tourism development, increased investment in infrastructure, digitalization, and vocational training and the consolidation of Romania's image as a competitive tourism destination on the international stage.

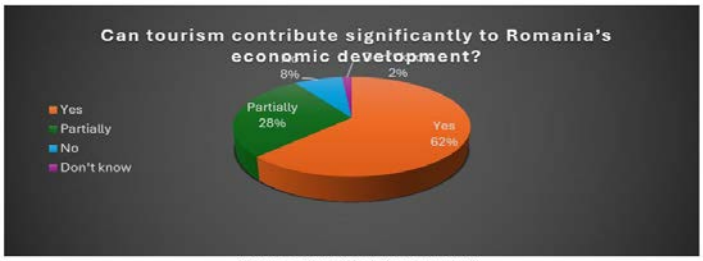


Figure 17. Tourism's capacity to develop Romania's economy

The findings indicate high macroeconomic optimism, as the target audience associates tourism with national prosperity. However, correlating this vision with previous data reveals a strategic contradiction: although respondents believe in tourism as an economic force (62%) and consider it attractive (51%), they reject academic professionalization in the field. This discrepancy suggests that respondents perceive tourism as a natural resource or a context that 'develops on its own,' failing to understand that achieving a major economic contribution requires highly qualified specialists, not just enthusiasm.

3. Digitalization of Educational Services in Tourism

Following quantitative and qualitative research regarding the deficit of students in faculties specializing in tourism in Romania, the digitalization of academic programs can revitalize institutional activity. In this context, marked by heightened economic volatility and a paradigm shift in the preferences of Generation Z, digitalization does not merely represent a modernization of pedagogical tools, but rather an institutional survival strategy.

Digitalization of educational services operates on three critical levels that can reverse the downward trend in enrollments:

Flexibility and Accessibility (The Phygital Model): The implementation of Hybrid Learning systems allows students to combine their studies with early practical experience. Accessibility is ensured by the digitalization of administrative processes (online enrollment, 24/7 e-learning platforms), which eliminates geographical barriers and facilitates the recruitment of international students or those from rural areas, thereby reducing the numerical deficit.

Alignment with Industry 4.0 (Smart Tourism): Faculties that integrate Property Management Systems (PMS), Global Distribution Systems (GDS), and Big Data analysis tools into their curricula become magnets for students. Consequently, students will no longer perceive the faculty as a purely theoretical space, but as a training hub for high-tech competencies, increasing the attractiveness of the study program.

Gamification and Immersive Experience: The use of Virtual Reality (VR) and Augmented Reality (AR) to simulate the management of a tourist destination or the operation of a resort transforms the learning process into an interactive experience.

The mechanism for mitigating the deficit through digitalization can be a process by which technology transforms enrollment volume, and it can be synthesized through the following correlation:

Digitalization Factors	Effect on the student	Result in indicators
Learning Personalization	Academic path adapted to individual pace (AI tutoring)	Decreased dropout rate (retention)
Digital Micro-certifications	Acquisition of competencies rapidly recognized in the market	Increased attractiveness for admission
Digital Networking	Access to mentors and global companies through dedicated platforms	Increased professional insertion rate

Tabel 1. The mechanism for mitigating the deficit through digitalization[4]

Thus, for tourism faculties, the digitalization of educational services is not a finite process, but an ecosystem. By transforming the student experience from a passive one into an active and technologically advanced one, higher education institutions can correct the current deficit.

4. Conclusions

There is a clear recognition of Romania's latent potential as a destination; however, the mediocrity of services is identified as the primary barrier to transforming this potential into real economic performance.

In addition to Romanian university programs in tourism, there is a vast offer across Europe, emphasizing modern competencies, internationalization, and practical relevance. The main challenges remain linked to the attractiveness of Romanian higher education and its adaptation to the labor market.

Integration with the actual economic environment, internships, and partnerships with the tourism sector can increase the relevance and demand for these programs.

The data reveal a prestige crisis in academic education within the tourism sector. Respondents value the field as promising (attractiveness over 50%) but perceive it as accessible without in-depth academic training. In the long term, this mindset may lead to a

[4] Compiled by the authors (UN Tourism, European Comision)

decline in the quality of tourism services in Romania, as the majority of those interested avoid higher specialization.

The lack of correlation between the industry's attractiveness and the desire to pursue higher education generates three strategic directions for intervention in the educational market:

- The Necessity of Academic Rebranding: Higher education institutions must demonstrate the added value of a university degree. Since respondents do not perceive the utility of continuing their studies, academic programs must focus on management and leadership competencies that basic practical experience alone cannot provide.
- Combating 'Competency Plateauing': Given that a segment of less than 8% possesses an in-depth understanding of career paths, there is a risk that the labor market will be flooded with personnel occupying entry-level positions who are unable to progress to executive roles due to a lack of strategic vision.
- Retention Strategies through Information: Tourism companies and universities must collaborate to transform the perception of a 'temporary job' into one of a 'sustainable career.' The fact that the field is attractive to 51% of youth represents a significant opportunity; however, this is squandered if it is not supported by a clear educational pathway that eliminates the uncertainty and lack of knowledge reported by the subjects.
- Digitalization of educational services – faculties that offer competencies in Smart Tourism Management through advanced digital platforms will always be prioritized over those using traditional methods, as these guarantee the relevance of the graduate on a globalized labor market.

In conclusion, the responses indicate that the future of Romanian tourism is perceived as generally favorable, yet characterized by caution and moderate expectations. To transform the existing potential into significant growth, consistent and predictable strategic interventions are required. Among these interventions, digitalization can serve as a key competitive advantage

References

[1] https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20250904-1

[2] https://www.contributors.ro/esti-tanar-si-cauti-sa-te-specializezi-in-turism/

[3] https://worldvision.ro/2024/03/20/romania-cei-mai-putini-absolventi-de-facultate-din-ue/

[4] https://stirileprotv.ro/educatie/fenomen-alarmant-in-educatie-universitatile-risca-sa-ramana-fara-studenti-in-2025-raspunsul-ministrului-educatiei.html

[5] https://www.libertatea.ro/educatie/admitere-toamna-2025-universitati-romania-locuri-neocupate-5442297

[6] https://www.integraledu.ro/news/tot-mai-multi-tineri-din-romania-aleg-sa-studieze-in-strainatate

[7] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://seaopenresearch.eu/Journals/articles/ MI_26_2.pdf

[8] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://ijbms.net/assets/files/1691803603.pdf

Bibliography

Faruk SEYITOĞLU, Ozan ATSIZ, Fazıl KAYA, Sedat TAŞ, *The two-way perspective of tourism undergraduates towards (post-)viral world: The future of tourism, and vocational development and career*, Journal of Hospitality, Leisure, Sport & Tourism Education, Elsevier, Volume 31, November 2022

Aleksandra GROBELNA, Magdalena BOGALECKA, *Tourism and Career Development in the Face of Seawater Threats: Understanding the Perspectives of Tourism and Hospitality Students from Coastal Areas*, Sustainability 2024, www.mdpi.com, https://doi.org/10.3390/su162310351

Dr. Sandeep PAATLAN, *Why Youngsters Are Losing Interest in Hospitality and Tourism Courses: A Statistical Perspective,* https://www.linkedin.com/posts/sandeep-paatlan-3a805562_why-youngsters-are-losing-interest-in-hospitality-activity-7348642419191541760-B8Fj/, PGDM Tourism, Chandigarh University, 2026

OECD, Centre for Educational Research and Innovation (CERI), *Smart Data and Digital Technology in Education: Artificial Intelligence, Learning Analytics and Beyond*, https://www.oecd.org/en/about/projects/smart-data-and-digital-technology-in-education--artifical-intelligence,-learning-analytics-and-beyond.html

https://www.youtube.com/watch?v=6W1K81FBjQY&t=49s, "Do Not Take A Travel And Tourism Course! 5 Reasons NOT To Study Travel And Tourism" course, 07.04.2026

https://www.zhihu.com/en/question/404233614- "*Why is the Tourism Management major at universities so unpopular?*"- Zhihu (知乎) is China's largest, high-quality knowledge-sharing platform and social question-and-answer (Q&A) website

www.bt.ase.ro - The Bucharest Academy of Economic Studies's official website

www.educations.com

www.edupedu.ro

https://gts.uoradea.ro/en/ -University of Oradea's official website

https://en.univ-ovidius.ro/ - Ovidius University of Constanța's official website

https://www.rau.ro – Romanian American University's official website.

www.unibuc.ro- The University of Bucharest's official website

www.at.unitbv.ro - Transilvania University of Brașov's official website

https://www.untourism.int/tourism-statistics/tourism-data-employment- UNWTO, *Tourism Education and Employment Trends Report*, 2023

https://www.valahia.ro/en/ -VALAHIA University of Târgoviște's official website.

https://wttc.org/research/economic-impact- WTTC, *Economic Impact Reports*, (2019–2023).

AI-BASED HOMEWORK ASSISTANCE AS A SERVICE INNOVATION IN PRIVATE EDUCATION: OPPORTUNITIES, PERCEIVED VALUE AND EXPECTED LEARNING OUTCOMES

Cristina DRAGAN[1]

Abstract

Homework remains one of the areas in which the distance between pedagogical intention and the family's everyday experience becomes most visible. Teachers generally see homework as necessary for consolidating knowledge, students often associate it with fatigue, blockage and monotony, while parents are frequently pushed into the difficult role of educational supporter, even when they do not have the time, patience or methodological tools required. In this context, the paper analyses the opportunity of using an AI-based homework assistant in private education, starting from the concept of Profesorul.ai/Virtual Teacher, developed as a digital educational solution and examined through a pilot study carried out in a private educational training setting. The research is designed as an exploratory pilot study conducted over four weeks, between February and March 2025, during an active school period. The study uses a simulated pilot dataset built on the beta-testing structure of Profesorul.ai and on the profile of the target users: 120 parents of students in grades IV-VIII, 80 students and 10 teachers/tutors. The analysis focuses on three dimensions: the opportunity of using the AI assistant, the perceived value for parents and students, and the expected learning outcomes. The findings indicate strong interest in a curriculum-controlled digital support tool, available outside regular teaching hours and designed to guide students without giving them direct answers. The contribution of the paper lies in proposing an integrated perspective on AI-based homework assistance as a service innovation in private education, at the intersection of artificial intelligence, educational management, educational marketing and customer relationship management.

Keywords: artificial intelligence, homework assistance, private education, service innovation, perceived value, educational CRM, student autonomy, expected learning outcomes

JEL Classification: M31, M15, I21, I23, O33

1. Introduction

[1] Lecturer PhD, Romanian -American University, Romania, cristina.dragan@rau.ro

The digital transformation of education is no longer only a matter of infrastructure or access to online platforms. In recent years, especially after the rapid diffusion of generative artificial intelligence tools, the debate has shifted towards the quality of educational support offered to students beyond direct interaction with the teacher. Intelligent tutoring systems and conversational applications are examined as resources for personalising learning, but also as sources of pedagogical, ethical and operational risks [1], [2]. At the same time, private education providers are increasingly evaluated not only for the quality of teaching, but also for their ability to provide continuity, flexibility and timely responses to the real needs of students and parents.

In private education, homework is not merely a pedagogical task placed between two meetings with the teacher. It becomes a visible part of the service experience: the parent observes whether the child understands, gets stuck, gives up, spends too much time on the task, or experiences tension at home. This creates a direct connection with educational marketing and customer relationship management. The continuity of educational support influences trust, satisfaction and parents' willingness to recommend the service.

The concept of Profesorul.ai/Virtual Teacher is relevant to this discussion because it proposes an AI assistant limited to the school curriculum, focused in the pilot stage on Mathematics and Romanian Language, with text, voice and image interaction. The tool is designed to support homework completion and test preparation through explanations, suggestions, examples and encouragement, without providing direct answers. This boundary is not a technical detail, but a pedagogical condition: the purpose is not to automate homework, but to keep the student active in the process of solving it.

The paper starts from the following assumption: an AI-based homework assistant can become a service innovation in private education only if it responds at the same time to an educational need, a relational expectation and an ethical condition. In other words, the tool must be useful for the student, acceptable for the parent and credible for the teacher. Therefore, the analysis does not stop at technological usefulness, but examines the role of the tool in the relationship between the educational provider, the student and the family.

The research problem is built around the paradox of homework. On the one hand, homework consolidates knowledge, creates work routines and develops responsibility. On the other hand, when the student does not understand the task or does not receive support in time, the same homework may become a source of frustration, postponement and temporary abandonment. For parents, this situation brings pressure, time consumption and, sometimes, conflict. For a private education provider, this difficulty is not secondary, because it can influence the perceived quality of the entire service.

The general objective of the paper is to analyse the extent to which an AI-based homework assistant, designed to provide step-by-step guidance, emotional support and explanations adapted to the student's level, can be perceived as a valuable service innovation in private education. The study examines opportunity, perceived value and expected learning outcomes, using a simulated pilot dataset built on the basis of a private educational training setting and the beta-testing structure of Profesorul.ai.

From a theoretical point of view, the paper is positioned at the intersection of research on artificial intelligence in education, service innovation, perceived value and customer relationship management. From an applied perspective, it proposes an interpretative framework for private education providers that aim to integrate AI tools without weakening the teacher's role and without encouraging students' dependence on automatic answers.

2. Literature review and theoretical framework

2.1 Artificial intelligence in education and intelligent tutoring

Recent literature on artificial intelligence in education highlights its capacity to provide rapid feedback, adapt to students' pace and support repetitive or individual tasks [3], [4]. Intelligent tutoring systems have long aimed to approximate some of the benefits of one-to-one interaction: adapted explanations, gradual exercises and immediate feedback. Generative models add a new dimension through natural conversation and the ability to reformulate the same explanation in different ways [5].

However, the adoption of AI in education cannot be treated as a simple technological upgrade. The literature points to risks related to inaccurate answers, excessive dependence, reduced cognitive effort, data privacy and insufficient pedagogical control [2], [6]. For this reason, international recommendations emphasise transparency, human oversight, safety and the alignment of AI tools with clear educational objectives [1], [7].

In pre-university education, these precautions are particularly important. An AI-based homework assistant should not function as a generator of final solutions, but as a support mechanism that provides hints, explains steps and encourages trying. In this logic, the student remains the author of the solution, while technology plays an accompanying rather than substitutive role.

2.2 Homework, learning continuity and student persistence

Homework has a recognised pedagogical function: consolidating knowledge, practising autonomy, organising individual work and preparing for assessment. In practice, however, its effectiveness depends on the support available when the student encounters difficulties. A misunderstood task or a wrongly started exercise can quickly turn a useful activity into a demotivating experience. From the student's perspective, the

problem is not always the amount of homework, but the moment of blockage and the lack of immediate feedback.

The working materials of Profesorul.ai describe this tension as a homework paradox: teachers consider homework essential for consolidation, students often perceive it as tiring or monotonous, and parents feel the pressure to intervene. Such intervention is not always simple. Many parents lack the time, emotional availability or methodical approach needed to explain a task without increasing tension. Homework thus becomes not only a school assignment, but also a test of family communication.

Learning continuity is therefore relevant for private educational services. Support received during a tutoring session may lose part of its effectiveness if the student is left alone with homework in the following days. An AI tool available when needed can reduce this discontinuity. Its value, however, is not measured only by the speed of response, but by its ability to keep the student engaged, clarify the steps and strengthen the feeling that continuation is possible.

2.3 Service innovation, perceived value and educational CRM

Service innovation does not only mean introducing a new technology, but reconfiguring processes and interactions through which beneficiaries perceive additional value. In private education, this value includes teaching, but it is not limited to it. Accessibility of support, trust, safety, communication and the feeling that the provider understands the practical difficulties of the family all matter. An AI-based homework assistant may therefore be analysed as an extension of the educational service, because it moves part of the support outside the formal teaching interval.

From the perspective of educational marketing, the parent is an indirect beneficiary, but a central evaluator of the service. Parents observe the child's stress, progress, autonomy and the time spent on homework. For this reason, the perceived value of a tool such as the Virtual Teacher includes functional, emotional and relational benefits: rapid support, reduced pressure, increased trust and the perception that the education provider offers solutions adapted to the real life of the family.

Customer relationship management in education involves more than administrative communication with parents. It includes understanding recurring needs, anticipating moments of friction and developing solutions that support trust. From this perspective, the Virtual Teacher can be read as an educational CRM tool: it does not merely add a digital function, but creates an additional contact point between the educational service and the family using it.

2.4 Ethical and pedagogical conditions for AI homework assistance

The use of AI in children's education requires firm boundaries. First, the tool must be aligned with the curriculum and must avoid content that is irrelevant or inappropriate for

the student's age. Second, it must respect the principle of complementarity: the human teacher remains responsible for designing learning, interpreting progress and validating the student's actual difficulties. Third, the solution must be designed so that it does not encourage copying or passivity, but guided effort.

These conditions are also supported by recent AI regulation. The European Artificial Intelligence Act, adopted in 2024, emphasises risk governance and protection in sensitive domains [8]. The present paper does not aim to provide a legal analysis, but it retains an important principle: in education, especially when users are minors, AI should be introduced gradually, verifiably and under human supervision.

Profesorul.ai is described in the working materials as an empathetic and patient assistant that does not provide direct answers, but offers useful guidance and encourages students to explore, learn and develop autonomy. This positioning forms the pedagogical basis of the paper and differentiates the tool from applications that deliver final solutions without the student's cognitive involvement.

3. Research objectives, questions and hypotheses

The general objective of the research is to analyse the extent to which an AI-based homework assistant, designed to provide step-by-step guidance, emotional support and explanations adapted to the student's level, can be perceived as a valuable service innovation in private education, with the potential to support homework completion, persistence, autonomy and parental satisfaction.

The specific objectives are to identify the main difficulties encountered by students and parents in the homework process; to evaluate the opportunity of introducing an AI-based homework assistant in private education; to analyse parents' perceived value; to investigate students' perception of step-by-step guidance; to evaluate teachers' perception of the complementary role of the tool; to analyse expected learning outcomes; and to formulate a conceptual framework regarding AI-based homework assistance as a service innovation.

The research questions address homework-related difficulties, the opportunity of using AI for students in grades IV-VIII, the influence of permanent availability and step-by-step guidance on perceived value, the role of the tool in reducing family stress, its capacity to support students when they get stuck, teachers' evaluation of its usefulness and limitations, and the expected learning outcomes.

Hypothesis	Statement
H1	The perceived need for additional homework support positively influences the acceptance of an AI-based homework assistant in private education.

H2	The perceived usefulness of the Virtual Teacher positively influences parents perceived value of the private educational service.
H3	Step-by-step guidance without providing direct answers positively influences the perceived autonomy of the student.
H4	The permanent availability of the AI assistant is positively associated with the perceived reduction of homework blocks.
H5	The empathetic and encouraging character of the assistant positively influences students motivation to continue homework when difficulties occur.
H6	Parents perception of safety, curricular relevance and controlled use positively influences trust in the assistant.
H7	The perceived value of the Virtual Teacher positively influences parents satisfaction and recommendation intention.
H8	Teachers/tutors perceive the AI assistant as useful in a complementary role, provided that it remains aligned with the school curriculum.

Table 1. Research hypotheses

4. Research methodology

The research was designed as an exploratory pilot study with a mixed quantitative and qualitative design. Its purpose is not to demonstrate a definitive educational impact, but to understand the conditions under which an AI-based homework assistant may be considered timely, acceptable and valuable. This distinction is important: the study measures perceptions, intentions to use and expected learning outcomes, not longitudinal academic performance.

The pilot study was configured for February-March 2025, over a period of four weeks, during a regular school interval. This timing is relevant because students have constant homework, current tests and revision activities, while the need for support appears naturally. The research was placed in a private educational training setting, with the testing of the Profesorul.ai concept as its starting point.

The analysed subjects were Mathematics and Romanian Language, as these were the subjects available in the testing stage of the Virtual Teacher. The platform allows interaction through text, voice or image, use from a phone, tablet, laptop or desktop, and task submission by writing, dictation, photographing or uploading images. These functions directly influenced the design of the questionnaire items and the feedback grid.

The research uses a simulated pilot dataset built on a private educational training setting, the beta-testing structure of Profesorul.ai and the profile of target users. This

methodological choice makes it possible to build a plausible empirical scenario for analysing opportunity and perceived impact. The dataset is not presented as a real measurement of academic performance, but as an exploratory instrument for potential adoption.

Respondent category	Number of respondents	Profile
Parents	120	Parents of students in grades IV-VIII
Students	80	Students in grade IV and lower-secondary education
Teachers/tutors	10	Teachers/tutors involved in testing
Total	210	Participants in the simulated pilot scenario

Table 2. Structure of the pilot sample

The quantitative component included structured questionnaires for parents and students. For parents, the items referred to the child's homework difficulties, the frequency of learning blocks, family time availability, homework-related stress, perceived usefulness of the AI assistant, safety, curricular relevance, perceived value, anticipated satisfaction and recommendation intention. For students, the items were phrased in accessible language and addressed homework blocks, preference for step-by-step explanations, comfort in interacting with a virtual assistant and willingness to continue the task when support is received.

The qualitative component consisted of collecting feedback from the teachers/tutors involved in testing, through an observation grid. It examined the correctness of explanations, the adequacy of responses to grade level, curriculum alignment, the capacity to guide without giving the direct answer, the quality of encouragement, usefulness for homework and revision, interpretation errors, voice transcription issues, response time and optimisation recommendations.

Quantitative data were analysed descriptively, using frequencies, percentages and mean scores on a five-point Likert scale. Qualitative data were analysed thematically, by grouping teachers' observations into categories such as pedagogical usefulness, curricular adequacy, autonomy, guidance, technical limitations, risks and recommendations. By combining the two components, the study provides a nuanced picture of potential adoption without claiming statistical generalisation.

Ethical considerations were integrated into the research design. Student participation presupposes parental consent, data are analysed in aggregated form, and the tool is presented as educational support, not as a replacement for the teacher. In addition, the

central characteristic of the Virtual Teacher is that it does not provide direct answers, but supports students in reaching the result through hints and explanations.

5. Results and analysis

The results presented in this section are based on the simulated pilot dataset described above. The analysis is organised around the three main dimensions of the research: the opportunity of using an AI-based homework assistant, perceived value for parents and students, and expected learning outcomes. Tables and graphics are used to make the dominant trends visible, while the interpretations emphasise the caution required when reading the data.

5.1 Respondent profile

Child grade	Number of parents	Percentage
Grade IV	24	20.0%
Grade V	26	21.7%
Grade VI	28	23.3%
Grade VII	22	18.3%
Grade VIII	20	16.7%
Total	120	100%

Table 3. Distribution of parents by child grade

The parent sample is relatively balanced across grades IV-VIII, with a slightly higher share for grades V-VI. This distribution is useful for analysis because homework volume increases in these grades and students move towards greater autonomy. This is precisely the area where blocks often appear: the child is old enough to work alone, but not always confident enough to overcome a difficult task without support.

School level	Number of students	Percentage
Grade IV	18	22.5%
Grades V-VI	34	42.5%
Grades VII-VIII	28	35.0%
Total	80	100%

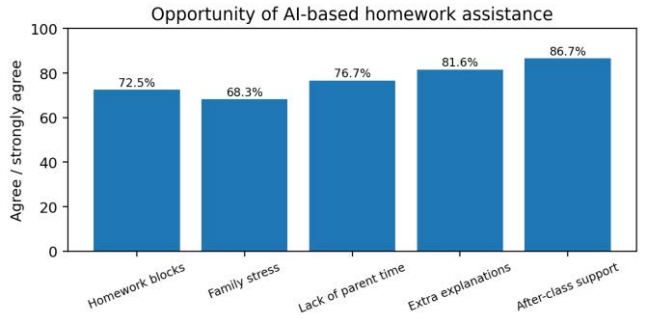
Table 4. Distribution of students by school level

Lower-secondary students represent 77.5% of the sample, which is appropriate for analysing the use of an AI-based homework tool. They already have a higher level of digital autonomy and face more complex tasks, especially in Mathematics and Romanian Language. The presence of fourth-grade students nevertheless preserves the link with the transition into a more demanding stage of schooling.

5.2 Opportunity of AI-based homework assistance

Item evaluated by parents	Agree / strongly agree	Mean score 1-5
My child frequently gets stuck with homework	72.5%	4.08
Homework generates stress in the family	68.3%	3.94
I do not always have time to help my child with homework	76.7%	4.21
My child needs additional explanations	81.6%	4.32
Support available outside class hours would be useful	86.7%	4.47

Table 5. Parents perception of homework-related difficulties



Graphic 1. Opportunity of using AI homework assistance from parents perspective

The results show that the main problem identified by parents is not the complete absence of educational support, but its discontinuity. More than three quarters of parents state that they do not always have time to help their child with homework, while more than 80% consider that the student needs additional explanations. The highest mean score, 4.47, is recorded for the usefulness of support available outside regular teaching hours.

These data indicate a service opportunity, not only a technological opportunity. An AI assistant may have value when it responds to a concrete need: the student gets stuck at a moment when the teacher is not available and the parent cannot intervene effectively.

In a private educational training setting, such a tool can complement the core service and reduce the gap between guided learning and individual work at home.

Item evaluated by students	Agree / strongly agree	Mean score 1-5
I sometimes do not know how to start homework	70.0%	3.96
I temporarily give up when I do not understand the task	58.7%	3.61
I would like to receive step-by-step explanations	83.8%	4.35
It helps me when someone gives hints, not the direct answer	78.8%	4.18
I would use a virtual assistant if it were easy to use	75.0%	4.06

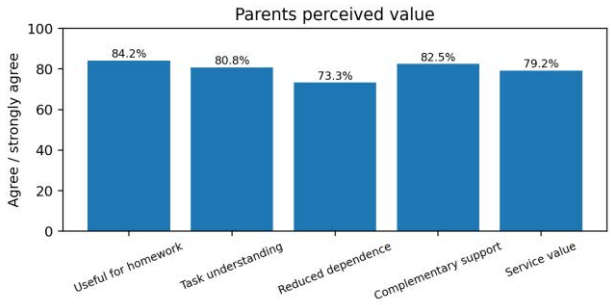
Table 6. Students perception of homework blocks

From the students' perspective, the results show that the initial block is a significant problem. 70% state that they sometimes do not know how to start a homework task, and 58.7% temporarily give up when they do not understand the requirement. At the same time, 83.8% prefer step-by-step explanations, while 78.8% appreciate hints instead of direct answers. This combination confirms the importance of guidance that supports the student's effort rather than replacing it.

5.3 Perceived value for parents

Item evaluated by parents	Agree / strongly agree	Mean score 1-5
The Virtual Teacher can be useful for homework completion	84.2%	4.39
It can help the child better understand tasks	80.8%	4.26
It can reduce the childs dependence on parent help	73.3%	4.02
It can complement the support provided by the teacher/tutor	82.5%	4.31
It can add value to the private educational service	79.2%	4.17

Table 7. Perceived usefulness and perceived service value



Graphic 2. Perceived value of Profesorul Virtual from parents perspective

The results indicate a favourable perception of the usefulness of the tool. More than 84% of parents consider the Virtual Teacher useful for homework completion, while 82.5% perceive it as complementary to the support provided by the teacher or tutor. This interpretation is important because it reduces the risk of positioning the tool as a substitute for the human teacher and places it instead in the area of controlled extension of the educational service.

From the perspective of educational marketing, perceived value is not a single indicator. It consists of functional value, through rapid homework support; emotional value, through the reduction of tension and blockage; and relational value, through increased trust that the education provider understands the real needs of the family. This interpretation explains why an apparently technological tool may have effects on satisfaction and loyalty.

Item evaluated by parents	Agree / strongly agree	Mean score 1-5
It is important that the tool is limited to the school curriculum	91.7%	4.68
It is important that the tool does not provide direct answers	85.0%	4.43
I would trust it more if the platform were tested by teachers	89.2%	4.61
I would trust it if it were used in a controlled educational setting	87.5%	4.55
Child safety in AI interaction is essential	95.0%	4.82

Table 8. Trust and safety conditions perceived by parents

The acceptance of AI in children's education is strongly conditioned by control, safety and curricular relevance. The highest mean score, 4.82, is obtained by the item regarding

child safety. This result shows that parents do not seek unrestricted AI interaction, but a controlled educational environment. In addition, 91.7% consider curriculum limitation important, while 89.2% state that testing by teachers would increase trust.

5.4 Expected learning outcomes from students perspective

Item evaluated by students	Agree / strongly agree	Mean score 1-5
I feel more encouraged when I receive step-by-step hints	81.3%	4.29
I would continue homework more easily if I received immediate help	85.0%	4.41
I feel less stressed when someone explains without criticising me	87.5%	4.56
I would have more confidence that I can solve tasks myself	76.3%	4.12
I would like the assistant to explain calmly several times	88.8%	4.63

Table 9. Expected educational outcomes from students perspective

Students particularly value patience, calmness and the possibility of receiving repeated explanations. The highest mean score, 4.63, is associated with the wish that the assistant explain calmly several times if needed. This result is significant because repeatable patience is one of the features through which an AI tool can complement human support without replacing it.

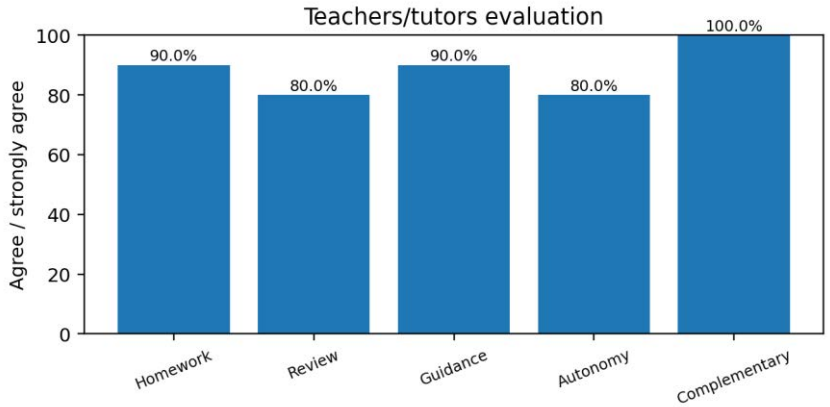
Another important result is that 85% of students state that they would continue homework more easily if they received immediate help. Based on this study, it cannot be claimed that the tool directly improves school performance. It can be argued, however, that it supports behaviours that precede performance: persistence, repeated attempts, clarification of requirements and self-confidence.

5.5 Teachers/tutors feedback

Evaluated dimension	Agree / strongly agree	Mean score 1-5
The tool is useful for homework support	90.0%	4.40
The tool may be useful for revision	80.0%	4.10

Step-by-step guidance is suitable for blocked students	90.0%	4.50
The tool may contribute to student autonomy	80.0%	4.20
The tool must be used as complementary, not as a substitute	100.0%	4.90

Table 10. Teachers/tutors evaluation of pedagogical utility



Graphic 4. Teachers/tutors evaluation of Profesorul Virtual

Observed limitation or risk	Teachers who mentioned it	Percentage
Possible errors in task interpretation	7 out of 10	70.0%
Need to verify explanations for complex exercises	6 out of 10	60.0%
Occasional problems in voice interaction	5 out of 10	50.0%
Risk of passive use by students	4 out of 10	40.0%
Need for continuous pedagogical monitoring	8 out of 10	80.0%

Table 11. Limits and risks identified by teachers/tutors

Teachers' feedback confirms the pedagogical potential of the tool, but also introduces a necessary note of caution. 90% of teachers consider the tool useful for homework support, while 100% emphasise that it must be used as a complementary instrument. This conclusion is essential for responsible AI integration in education: technology may

support explanation and practice, but it cannot replace pedagogical judgement, the human relationship and contextual evaluation by the teacher.

The risks identified by teachers are relevant for further development. 70% mentioned possible errors in task interpretation, while 80% indicated the need for continuous pedagogical monitoring. These results do not invalidate the opportunity of the tool; rather, they define the conditions for implementation: testing, optimisation, curricular limitation, expert verification and transparent communication with parents.

5.6 Hypotheses assessment

Hypothesis	Result	Synthetic argument
H1	Supported	The need for additional support and the usefulness of after-class support show high values.
H2	Supported	Perceived usefulness is associated with perceived value of the educational service.
H3	Supported	Students and parents appreciate guidance without direct answers.
H4	Supported	Immediate help is associated with continuing homework when blocks occur.
H5	Supported	Calm and encouraging interaction is linked to motivation and stress reduction.
H6	Supported	Safety, curricular control and teacher testing increase trust.
H7	Supported	Perceived value supports satisfaction and recommendation intention.
H8	Supported	Teachers consider the tool useful, but only in a complementary role.

Table 12. Synthetic assessment of research hypotheses

The hypotheses assessment shows support for all formulated directions, within the limits of an exploratory pilot study based on simulated data. Interpretation must therefore remain cautious: the results indicate high adoption potential and favourable perceived value, not a definitive validation of impact on academic performance. This distinction is important for the credibility of the study and for the design of future research.

6. Discussion: AI-based homework assistance as service innovation

The results support the idea that the Virtual Teacher can be analysed as a service innovation in private education. The innovation does not lie only in the use of AI, but in the way technology changes the beneficiary experience. For the student, support

becomes more continuous because it is no longer limited to the lesson or to the parent's availability. For the parent, the service becomes more valuable because it reduces homework-related pressure and increases the feeling of safety. For the teacher, the tool may take over part of the repetitive support without replacing the role of pedagogical design and validation.

Based on the results, a conceptual model of AI-based homework assistance in private education can be proposed. The model starts with the need for additional support and the frequency of learning blocks. These elements generate interest in a permanently available tool. The value of the tool then depends on four characteristics: step-by-step guidance, empathetic interaction, adaptation to the student's level and curricular limitation. These characteristics influence student persistence, stress reduction, autonomy and parental satisfaction. Finally, parental satisfaction and the perception of innovation may support loyalty and recommendation intention.

From a CRM perspective, the AI assistant becomes an additional contact point between the institution and the family. Even if the actual interaction takes place between the student and the platform, the value is also evaluated by the parent. Implementation should therefore be accompanied by clear communication: what the tool can do, what it should not do, why it does not provide direct answers, how it is tested, how data are protected and how curriculum alignment is ensured.

From a pedagogical perspective, one of the most important observations is that students appreciate repeated explanations and the absence of criticism. This result suggests that homework abandonment may be linked to emotional and relational factors, not only cognitive ones. A correctly calibrated empathetic AI assistant can create a space for trying without embarrassment and without fear of immediate judgement. However, this advantage must be balanced against the risk of dependence and the need to preserve student effort.

From a technical perspective, teachers' feedback shows that responsible implementation requires continuous monitoring. Interpretation errors, voice difficulties and insufficiently calibrated explanations may quickly affect trust. Therefore, the development of such a tool should include testing protocols, feedback collection, curriculum updates and mechanisms through which teachers can validate and improve responses.

7. Conclusions

The paper analysed the opportunity of using an AI-based homework assistant as a service innovation in private education, starting from the concept of Profesorul.ai/Virtual Teacher, examined in a private educational training setting. The research was designed as an exploratory pilot study based on a simulated dataset, with 120 parents, 80 students and 10 teachers/tutors. The results indicate a significant opportunity, favourable

perceived value and positive expectations regarding persistence, autonomy and reduced homework-related stress.

The first conclusion is that homework represents a critical area of the educational experience, where the need for support frequently appears outside formal teaching time. More than 80% of parents consider that the student needs additional explanations, while 86.7% consider support available outside regular teaching hours useful. This finding confirms the existence of a real opportunity for AI-based assistance, provided that the tool is responsibly integrated.

The second conclusion is that parents' perceived value depends on safety, curricular control and the complementary role of the tool. Parents do not respond favourably to an unrestricted AI solution, but to a tool tested by teachers, adapted to age and designed to guide without providing direct answers. In this respect, positioning the Virtual Teacher as an assistant rather than a substitute for the teacher is essential.

The third conclusion is that students value calm, encouraging and repeatable explanations. The results suggest that an AI assistant may reduce temporary homework abandonment by offering immediate support at moments of blockage. The expected impact therefore does not refer only to the correctness of homework, but to learning behaviours such as persistence, confidence and autonomy.

The fourth conclusion concerns the role of teachers. Their feedback validates the usefulness of the tool for homework and revision, but also underlines the need for pedagogical monitoring. AI can support the educational process, but pedagogical decisions, interpretation of progress and the educational relationship remain the responsibility of the human teacher.

The contribution of the paper consists in proposing an integrated perspective on AI-based homework assistance as a service innovation in private education. This perspective connects artificial intelligence with educational marketing, customer relationship management and expected learning outcomes. Future research should include a longitudinal study with real usage data, comparison of performance before and after tool integration, extension to other subjects and testing of the model on larger samples.

References

[1] UNESCO - Guidance for Generative AI in Education and Research - UNESCO Publishing. ISBN 978-92-3-100612-8. 2023

[2] European Commission - Ethical Guidelines on the Use of Artificial Intelligence and Data in Teaching and Learning for Educators - Publications Office of the European Union. ISBN 978-92-76-57564-2. 2022

[3] Zawacki-Richter O., Marin V.I., Bond M., Gouverneur F. - Systematic Review of Research on Artificial Intelligence Applications in Higher Education - International Journal of Educational Technology in Higher Education, 16, article 39. ISSN 2365-9440. 2019

[4] Chen L., Chen P., Lin Z. - Artificial Intelligence in Education: A Review - IEEE Access, volume 8, pp. 75264-75278. ISSN 2169-3536. 2020

[5] Kasneci E., Sessler K., Kuchemann S., Bannert M., Dementieva D., Fischer F., Gasser U., Groh G., Gunnemann S., Hullermeier E., Krusche S., Kutyniok G., Michaeli T., Nerdel C., Pfeffer J., Poquet O., Sailer M., Schmidt A., Seidel T., Stadler M., Weller J., Kuhn J., Kasneci G. - ChatGPT for Good? On Opportunities and Challenges of Large Language Models for Education - Learning and Individual Differences, 103, 102274. ISSN 1041-6080. 2023

[6] Lo C.K. - What Is the Impact of ChatGPT on Education? A Rapid Review of the Literature - Education Sciences, 13(4), 410. ISSN 2227-7102. 2023

[7] OECD - Is Education Losing the Race with Technology? AI's Progress in Maths and Reading - Educational Research and Innovation. ISBN 978-92-64-58497-0. OECD Publishing. 2023

[8] European Parliament and Council of the European Union - Regulation (EU) 2024/1689 laying down harmonised rules on artificial intelligence - Official Journal of the European Union. 12 July 2024

[9] Holmes W., Tuomi I. - State of the Art and Practice in AI in Education - European Journal of Education, 57(4), pp. 542-570. ISSN 0141-8211. 2022

[10] Crompton H., Burke D. - Artificial Intelligence in Higher Education: The State of the Field - International Journal of Educational Technology in Higher Education, 20, article 22. ISSN 2365-9440. 2023

[11] Dwivedi Y.K., Kshetri N., Hughes L., et al. - So What if ChatGPT Wrote It? Multidisciplinary Perspectives on Opportunities, Challenges and Implications of Generative Conversational AI for Research, Practice and Policy - International Journal of Information Management, 71, 102642. ISSN 0268-4012. 2023

[12] Przegalinska A., Ciechanowski L., Stroz A., Gloor P., Mazurek G. - In Bot We Trust: A New Methodology of Chatbot Performance Measures - Business Horizons, 62(6), pp. 785-797. ISSN 0007-6813. 2019

[13] Wach K., Duong C.D., Ejdys J., Kazlauskaitė R., Korzynski P., Mazurek G., Paliszkiewicz J., Ziemba E. - The Dark Side of Generative Artificial Intelligence: A Critical Analysis of Controversies and Risks of ChatGPT - Entrepreneurial Business and Economics Review, 11(2), pp. 7-30. ISSN 2353-883X. 2023

[14] Akgun S., Greenhow C. - Artificial Intelligence in Education: Addressing Ethical Challenges in K-12 Settings - AI and Ethics, 2, pp. 431-440. ISSN 2730-5961. 2022

[15] Zhang K., Aslan A.B. - AI Technologies for Education: Recent Research and Future Directions - Computers and Education: Artificial Intelligence, 2, 100025. ISSN 2666-920X. 2021

[16] Internal project materials - Profesorul.ai: landing-page sections and service concept document - unpublished internal document. 2025

[17] Internal project materials - Profesorul.ai beta-testing guide for teachers/tutors - unpublished internal document. 2025

[18] Internal project materials - Profesorul.ai beta-testing tips for parents and students - unpublished internal document. 2025

Bibliography

Akgun S., Greenhow C. - Artificial Intelligence in Education: Addressing Ethical Challenges in K-12 Settings - AI and Ethics, 2, pp. 431-440. ISSN 2730-5961. 2022

Baidoo-Anu D., Ansah L.O. - Education in the Era of Generative Artificial Intelligence: Understanding the Potential Benefits of ChatGPT in Promoting Teaching and Learning - Journal of AI, 7(1), pp. 52-62. 2023

Chen L., Chen P., Lin Z. - Artificial Intelligence in Education: A Review - IEEE Access, volume 8, pp. 75264-75278. ISSN 2169-3536. 2020

Crompton H., Burke D. - Artificial Intelligence in Higher Education: The State of the Field - International Journal of Educational Technology in Higher Education, 20, article 22. ISSN 2365-9440. 2023

Dwivedi Y.K., Kshetri N., Hughes L., et al. - So What if ChatGPT Wrote It? Multidisciplinary Perspectives on Opportunities, Challenges and Implications of Generative Conversational AI for Research, Practice and Policy - International Journal of Information Management, 71, 102642. ISSN 0268-4012. 2023

European Commission - Ethical Guidelines on the Use of Artificial Intelligence and Data in Teaching and Learning for Educators - Publications Office of the European Union. ISBN 978-92-76-57564-2. 2022

European Parliament and Council of the European Union - Regulation (EU) 2024/1689 laying down harmonised rules on artificial intelligence - Official Journal of the European Union. 12 July 2024

Holmes W., Tuomi I. - State of the Art and Practice in AI in Education - European Journal of Education, 57(4), pp. 542-570. ISSN 0141-8211. 2022

Lo C.K. - What Is the Impact of ChatGPT on Education? A Rapid Review of the Literature - Education Sciences, 13(4), 410. ISSN 2227-7102. 2023

OECD - Is Education Losing the Race with Technology? AI's Progress in Maths and Reading - Educational Research and Innovation. ISBN 978-92-64-58497-0. OECD Publishing. 2023

Przegalinska A., Ciechanowski L., Stroz A., Gloor P., Mazurek G. - In Bot We Trust: A New Methodology of Chatbot Performance Measures - Business Horizons, 62(6), pp. 785-797. ISSN 0007-6813. 2019

Sharples M. - Towards Social Generative AI for Education: Theory, Practices and Ethics - Learning: Research and Practice, 9(2), pp. 159-167. ISSN 2373-5087. 2023

UNESCO - Guidance for Generative AI in Education and Research - UNESCO Publishing. ISBN 978-92-3-100612-8. 2023

Wach K., Duong C.D., Ejdys J., Kazlauskaitė R., Korzynski P., Mazurek G., Paliszkiewicz J., Ziemba E. - The Dark Side of Generative Artificial Intelligence: A Critical Analysis of Controversies and Risks of ChatGPT - Entrepreneurial Business and Economics Review, 11(2), pp. 7-30. ISSN 2353-883X. 2023

Zhang K., Aslan A.B. - AI Technologies for Education: Recent Research and Future Directions - Computers and Education: Artificial Intelligence, 2, 100025. ISSN 2666-920X. 2021. DOI: 10.1016/j.caeai.2021.100025

Internal project materials

Internal project materials - Profesorul.ai beta-testing guide for teachers/tutors - unpublished internal document. 2025

Internal project materials - Profesorul.ai: landing-page sections and service concept document - unpublished internal document. 2025

Internal project materials - Profesorul.ai beta-testing tips for parents and students - unpublished internal document. 2025

SMART RAPID-DEPLOY MODULAR HOUSING AS URBAN RESILIENCE INFRASTRUCTURE - A PATENT-INFORMED FRAMEWORK FOR CONNECTED SMART CITIES

Eugen Gabriel GARAIS[1]

Abstract

Rapid urbanization, climate-related disruptions, and increasing socio-economic volatility demand fast, scalable, and resilient housing solutions within smart city ecosystems. This paper proposes a hybrid physical–digital framework for rapid-deploy modular housing, based on a patented prefabricated, foldable, and transportable construction system (Romanian Patent RO 106900 B1), extended through IoT-enabled monitoring, low-power communication protocols (e.g., LoRaWAN, NB-IoT), and cloud-based coordination. To strengthen practical applicability, the study introduces a pilot deployment scenario of a modular housing cluster, illustrating deployment workflows, system interoperability, and real-time data integration within a smart city context. A structured set of Key Performance Indicators (KPIs) is defined and exemplified across operational efficiency, sustainability, service quality, and socio-economic impact, alongside an energy autonomy layer based on photovoltaic generation and local storage. A comparative perspective with conventional temporary housing approaches highlights improvements in deployment speed, scalability, and adaptability. By bridging a historically grounded engineering solution with contemporary digital infrastructures and an applied scenario, the paper contributes a scalable model for resilient and data-driven urban housing within smart cities.

Keywords: Smart cities; rapid-deploy housing; modular prefabrication; urban resilience; IoT integration; cloud data sharing; smart infrastructure

JEL Classification Codes: R11; R58; O18; Q01

1. Introduction

Cities worldwide face increasing pressure from rapid urbanization, climate change, demographic shifts, and socio-economic volatility. These dynamics strain urban infrastructure, especially in domains directly affecting human well-being, such as housing and emergency response. In this context, the smart city paradigm offers a framework for

[1] PhD, Lecturer, School of Computer Science for Business Management, Romanian-American University, Romania, gabriel.garais@rau.ro

improving urban adaptability, efficiency, and resilience through digital technologies and data-driven governance [1].

Despite major advances in mobility, energy, and environmental monitoring, housing remains insufficiently integrated into smart city infrastructures [1]. Traditional housing systems are characterized by long development cycles, high capital requirements, and limited flexibility, making them poorly suited to emergency and transitional contexts. At the same time, modular and prefabricated housing has gained renewed attention because of its speed, transportability, and scalability, yet most existing solutions remain disconnected from sensor networks, cloud platforms, and coordinated governance mechanisms [3].

This paper argues that rapid-deploy modular housing should be reconceptualized as a connected urban infrastructure service within smart city ecosystems. Building upon a patented foldable and transportable construction system developed by Romanian engineer Nicolae Mihoci (RO 106900 B1), it proposes a hybrid physical–digital framework integrating modular units, IoT-based monitoring, low-power communications, and cloud coordination [4]. To strengthen practical applicability, the paper introduces a pilot deployment scenario of a modular housing cluster and operationalizes a set of Key Performance Indicators (KPIs) covering deployment efficiency, sustainability, service quality, and socio-economic impact. The study thus contributes a scalable model for resilient and data-driven urban housing within contemporary smart cities.

2. Smart city context and related work

The concept of the smart city has evolved into a socio-technical framework integrating digital technologies, physical infrastructure, and governance mechanisms to improve urban efficiency, sustainability, and quality of life. More recent research emphasizes resilience as a key dimension of smart cities, focusing on the capacity of urban systems to respond to disruptions while maintaining essential services.

In parallel, a substantial body of work addresses post-disaster housing and emergency sheltering, highlighting the importance of rapid deployment, adaptability, and user-centered design [2]. Prefabricated and modular construction systems are widely recognized for their ability to reduce construction time, improve logistics, and support scalable deployment in crisis contexts. Similarly, contemporary modular housing research emphasizes off-site manufacturing, standardization, and lifecycle efficiency.

However, despite these advances, modular housing solutions are typically treated as isolated construction systems rather than integrated components of smart city infrastructures. Existing approaches rarely incorporate IoT-enabled monitoring, interoperable data platforms, or coordinated governance mechanisms that would enable real-time management and system-level optimization [4].

This gap between physical modular housing systems and digital smart city infrastructures motivates the present study, which proposes an integrated framework positioning rapid-deploy modular housing as a connected and adaptive urban infrastructure layer.

3. Patent-informed modular housing system

The proposed framework builds upon a patented prefabricated modular construction solution developed by Romanian engineer Nicolae Mihoci (Romanian Patent RO 106900 B1), designed to enable rapid deployment, efficient transport, and scalable housing delivery. The concept was further extended through a patent application initiated in Germany in 1989 for a "transportable house made of prefabricated elements" (Transportfähiges Haus aus vorgefertigten Elementen), reflecting its early international development trajectory. This study focuses on the system's engineering logic and operational advantages within smart city environments.

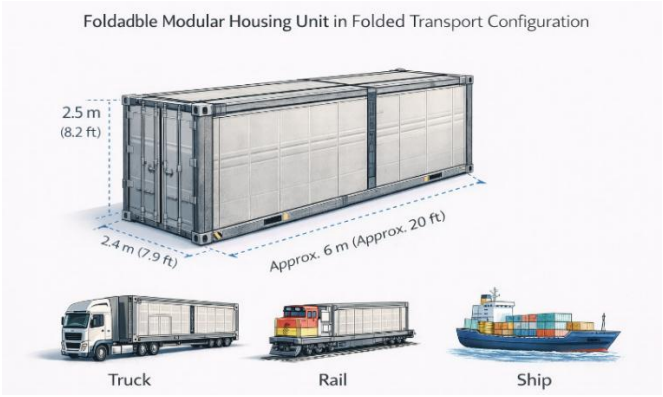


Figure 1 - Modular housing unit in its folded configuration

The core innovation lies in a foldable structural configuration that allows each unit to be transported in a compact form and deployed on-site through a controlled mechanical unfolding process. The module integrates structural elements, enclosure components, and preconfigured functional zones into a single transportable unit, minimizing on-site construction requirements.

This folding mechanism significantly reduces transport volume compared to conventional prefabricated modules, enabling multiple units to be delivered using standard logistics infrastructure. As a result, deployment efficiency is improved both in terms of time and cost [1]. Once on-site, the unit can be unfolded and stabilized with minimal equipment, allowing rapid transition from transport to operational use.

From an operational perspective, the system supports a full lifecycle model including prefabrication, transport, rapid deployment, relocation, and reuse [3]. This transforms

housing from a fixed asset into a mobile infrastructure resource, suitable for dynamic allocation in emergency or high-variability contexts.

In addition, the modular design incorporates standardized interfaces for connection to external systems such as energy supply, water, sanitation, and communication networks. This ensures interoperability with both temporary and permanent infrastructure, facilitating integration into broader urban systems.

Figure 1 illustrates the modular housing unit in its folded configuration, highlighting the compact transport form and structural arrangement that enables efficient logistics and rapid deployment.

4. System architecture: physical–digital integration

4.1 Physical and Functional Layer

Within the proposed framework, the modular housing unit is reconceptualized as a deployable urban infrastructure component rather than a standalone construction element. Each unit functions as a standardized, reusable module designed for rapid installation, relocation, and integration into diverse urban contexts, including emergency settlements and temporary extensions of existing urban areas.

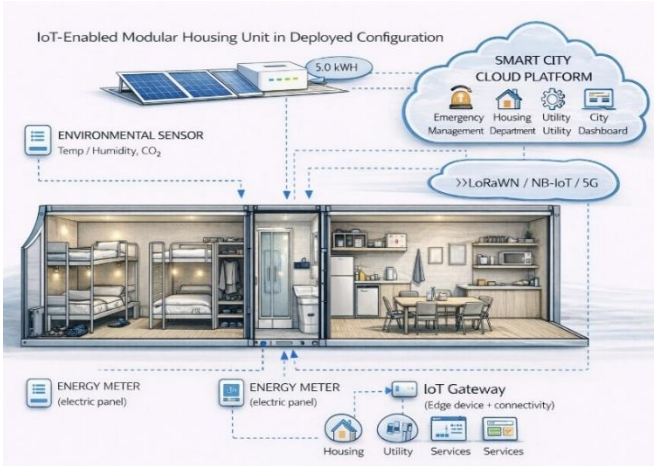


Figure 2 - Modular housing unit in its deployed configuration

Figure 2 illustrates the modular housing unit in its deployed configuration, highlighting both spatial organization and functional layout.

The modular configuration supports clustering, enabling the formation of adaptable micro-communities that can scale according to demand. Internally, the unit is organized into compact functional zones supporting essential activities such as sleeping, hygiene, storage,

and basic domestic use. Space optimization is achieved through multifunctional elements, including bunk beds, foldable furniture, and integrated storage systems, allowing multiple occupants to be accommodated efficiently within a limited footprint [3].

4.2 Digital and IoT Architecture

To enable integration within smart city ecosystems, each modular unit is equipped with an IoT-based monitoring system that captures key operational and environmental parameters. Typical sensor configurations include temperature and humidity sensors (e.g., BME280), air quality sensors (e.g., CO_2 monitoring), smart energy meters, and occupancy detection through PIR sensors.

Data is collected locally and transmitted through a hybrid communication architecture combining low-power wide-area technologies such as LoRaWAN or NB-IoT with higher-bandwidth solutions (4G/5G), depending on infrastructure availability (ITU, 2017). A local gateway aggregates data from multiple units and ensures secure transmission to cloud-based platforms.

At the platform level, data is processed and visualized through dashboards that support real-time monitoring, predictive maintenance, and coordinated resource management across the housing cluster. This architecture enables operational visibility and data-driven decision-making at both local and municipal levels (Chichernea, 2011; Chichernea, 2015; NIST, 2022).

4.3 Energy, Governance, and Security Integration

To enhance resilience, the system incorporates decentralized energy generation through photovoltaic panels (typically 1.5–3 kW per unit) combined with local storage (approximately 5 kWh). This configuration enables partial energy autonomy, particularly in off-grid or infrastructure-constrained environments, while also supporting hybrid operation in grid-connected contexts (Ceranic et al., 2018).

From a governance perspective, the system is designed to operate within a multi-stakeholder environment involving municipal authorities, emergency services, and infrastructure providers. Interoperability is ensured through standardized data formats and communication interfaces, enabling integration with existing smart city platforms (ITU, 2017; NIST, 2022).

Security and privacy considerations are addressed through a security-by-design approach, including encrypted communication, device authentication, and controlled data access. Particular attention is given to data protection in emergency contexts, where sensitive information related to vulnerable populations must be handled through anonymization and strict access policies in compliance with regulatory frameworks such as GDPR.

5. PILOT CASE STUDY: MODULAR HOUSING CLUSTER DEPLOYMENT

5.1 Scenario overview: modular micro-community deployment

To demonstrate practical applicability, a pilot deployment scenario is defined based on a modular housing cluster composed of ten units. The scenario simulates a rapid-response intervention in a post-disaster context requiring the establishment of a temporary yet functional living environment within a short timeframe (UNDRR, 2015; Ginigaddara et al., 2023).

Six units are allocated for residential use, accommodating approximately 3–4 occupants per unit (total capacity: 18–24 individuals), while four units serve support functions, including a medical point, a childcare or educational space, a shared social/dining unit, and an administrative coordination unit. Each unit provides an estimated usable area of 18–25 m^2, optimized through compact design solutions such as bunk beds, foldable furniture, and integrated storage systems.

5.2 Deployment workflow and logistics

The foldable configuration enables efficient transport and rapid installation [3]. Approximately 4–6 units can be transported per standard flatbed truck, depending on configuration and regulations. On-site deployment involves mechanical unfolding, positioning, and stabilization, requiring approximately 2–4 hours per unit.

Connection to essential utilities, including temporary power, water, and sanitation, can be completed within an additional 1–2 hours per unit through standardized interfaces. As a result, a full cluster of ten units can become operational within 24–48 hours, significantly faster than conventional temporary housing solutions.

5.3 IoT ecosystem and inter-unit connectivity

Each unit is equipped with an IoT monitoring system including environmental sensors (temperature, humidity, CO_2), smart energy meters, and occupancy detection (PIR sensors), with optional extensions such as door/window sensors and leak detection [2].

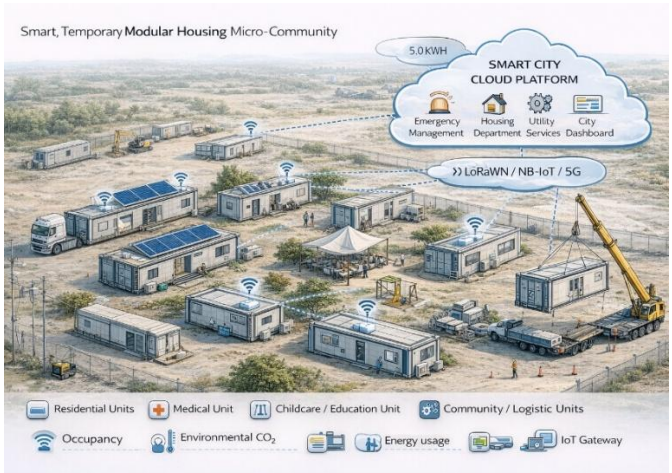


Figure 3 - Modular housing cluster

Data is transmitted through a hybrid communication architecture combining LoRaWAN for low-power, long-range connectivity with NB-IoT or 4G/5G where available. A local gateway aggregates data at cluster level and transmits it to a cloud platform, where it is processed and visualized through dashboards.

This enables real-time monitoring of key parameters, including indoor environmental conditions (18–26°C; CO_2 < 1000 ppm), energy consumption (kWh/day), and occupancy patterns, transforming the cluster into a coordinated digital system supporting data-driven management.

Figure 3 illustrates the deployment scenario, including units in different operational stages and the associated data communication flows.

5.4 Energy layer and comparative performance

Each unit can integrate a photovoltaic system with an installed capacity of approximately 1.5–3 kW and a local battery storage of around 5 kWh. This enables partial energy autonomy, supporting essential loads such as lighting, ventilation, and device charging, with autonomy of approximately 12–24 hours depending on usage [1].

Compared to conventional temporary housing, the system offers significant advantages (Ginigaddara et al., 2023; Nguyen et al., 2022), including deployment time reduction (from weeks to 24–48 hours), improved transport efficiency (4–6 units per truck), reusability across multiple cycles, real-time monitoring capabilities, and enhanced resilience through decentralized energy systems.

5.5 KPI operationalization within the pilot scenario

The pilot scenario enables direct mapping of KPIs to measurable variables (ISO 37120, 2018; ITU, 2017; NIST, 2022), including deployment time (<4 hours/unit), total cluster

readiness (<48 hours), energy consumption (3–6 kWh/day per unit), environmental conditions (18–26°C; CO_2 < 1000 ppm), occupancy rate, and system uptime.

These indicators are continuously monitored through the IoT infrastructure, providing a structured basis for performance evaluation and future empirical validation.

6. Performance evaluation framework and scalability

6.1 KPI framework and evaluation dimensions

To support systematic assessment, the proposed system is evaluated through a structured set of Key Performance Indicators (KPIs) covering four core dimensions: deployment efficiency, environmental performance, service quality, and socio-economic impact (ISO 37120, 2018; NIST, 2022; ITU, 2017).

Deployment efficiency focuses on rapid installation and operational readiness, including metrics such as deployment time per unit (<4 hours) and full cluster activation (<48 hours). Environmental performance evaluates energy consumption (3–6 kWh/day per unit), indoor conditions (18–26°C; CO_2 < 1000 ppm), and integration of renewable energy sources.

Service quality addresses occupant-related parameters, including occupancy rate, perceived comfort, and system uptime, while socio-economic impact considers cost efficiency, reusability across multiple deployment cycles, and local economic integration.

The KPIs are operationalized through measurable variables collected via the IoT infrastructure, enabling continuous monitoring and real-time evaluation.

Table 1 presents the operationalized KPI framework, including measurement methods, frequency, target benchmarks, and responsible entities, ensuring alignment with SMART performance criteria.

TABLE 1. KPI FRAMEWORK FOR MODULAR SMART HOUSING SYSTEM

Category	KPI	Measurement Method / Data Source	Frequency	Target / Benchmark	Responsible Entity
Deployment Efficiency	Time to install per unit	Manual log / deployment records	Per deployment	< 4 hours / unit	Deployment team / Site operator
	Total cluster deployment time	Project timeline tracking	Per deployment	< 48 hours (10 units)	Project coordinator
	Transport efficiency	Units per transport cycle	Per deployment	4–6 units / truck	Logistics operator
Energy & Environment	Daily energy consumption	Smart meter (Modbus / IoT)	Daily	3–6 kWh / unit	Energy operator
	Renewable energy contribution	PV production vs consumption	Daily	> 50% (context-dependent)	Energy operator

Category	KPI	Measurement Method / Data Source	Frequency	Target / Benchmark	Responsible Entity
	Indoor temperature	Environmental sensors (BME280)	Continuous	18–26°C	System monitoring unit
	CO_2 concentration	CO_2 sensors (MH-Z19)	Continuous	< 1000 ppm	System monitoring unit
Service Quality	Occupancy rate	PIR sensors / manual input	Daily	70–100% (optimal usage)	Site administrator
	Service availability (power, water, sanitation)	System status logs	Continuous	> 95% uptime	Infrastructure operator
	IoT system uptime	Network & platform monitoring	Continuous	> 98% uptime	IT / platform operator
Socio-Economic Impact	Cost per unit (deployment)	Financial estimation / project data	Per deployment	Lower than conventional solutions (order-of-magnitude)	Project manager
	Scalability rate	Units deployed per day	Per deployment	5–10 units/day (cluster scale)	Deployment coordinator
	Reusability index	Number of reuse cycles per unit	Lifecycle tracking	≥ 3 deployment cycles	Asset manager

6.2 Data integration and monitoring workflow

All KPI-related data is collected through distributed sensors at unit level and aggregated at cluster level via local gateways. The data is transmitted to cloud-based platforms where it is processed, stored, and visualized through interactive dashboards (Li et al., 2021; Chichernea, 2011; Chichernea, 2015).

This architecture supports both real-time operational monitoring and historical analysis, enabling predictive maintenance, anomaly detection, and optimization of resource allocation. The integration of IoT data with decision-support systems allows stakeholders to dynamically adjust deployment strategies and improve system performance over time.

6.3 Scalability and replicability

The proposed system is inherently scalable [5], allowing incremental expansion from small clusters (5–10 units) to larger deployments (50–100+ units) depending on demand. Standardized modular design, interoperable communication protocols, and cloud-based coordination enable replication across different urban contexts, including post-disaster environments, temporary workforce housing, and infrastructure-constrained areas.

From a logistical perspective, scalability is supported by transport efficiency (4–6 units per truck), rapid deployment capabilities, and reusability across multiple operational cycles. From a digital perspective, the architecture supports horizontal scaling of IoT devices and cloud resources without significant structural modifications (Li et al., 2021; Parracho et al., 2025).

6.4 Limitations and future work

Despite its advantages, the proposed framework requires further validation through real-world deployment. Future work will focus on large-scale pilot implementations, integration with municipal smart city platforms, and refinement of KPI benchmarks based on empirical data.

Additional research directions include optimization of energy autonomy, enhancement of user-centric service indicators, and exploration of AI-driven predictive models for deployment planning and resource management.

7. Conclusions

This paper has proposed a novel framework for reconceptualizing rapid-deploy modular housing as an integrated urban infrastructure service within smart city ecosystems. By combining a patented foldable construction system with IoT-enabled monitoring, decentralized energy solutions, and cloud-based coordination, the study advances a hybrid physical–digital approach to resilient urban housing.

The pilot deployment scenario demonstrates the practical feasibility of the system, highlighting significant improvements in deployment speed (24–48 hours for a functional cluster), transport efficiency (4–6 units per truck), and operational adaptability. The integration of IoT technologies enables continuous monitoring of environmental conditions, energy consumption, and occupancy, supporting data-driven decision-making and improved service quality.

Furthermore, the proposed KPI framework provides a structured method for evaluating system performance across multiple dimensions, including efficiency, sustainability, and socio-economic impact. This contributes to bridging the gap between conceptual smart city models and deployable, measurable infrastructure solutions [1] [5].

From a broader perspective, the study positions modular housing not as a temporary or isolated solution, but as a scalable and replicable component of future urban systems. Its applicability extends beyond post-disaster scenarios to include temporary workforce housing, rapid urban expansion, and infrastructure-constrained environments.

Future research will focus on large-scale pilot implementations, integration with municipal digital platforms, and the development of AI-driven optimization models for deployment planning and resource management.

Overall, the proposed framework contributes to the advancement of adaptive, resilient, and data-driven urban infrastructure, aligning with the evolving needs of contemporary smart cities.

References

[1] Caragliu, A., Del Bo, C., & Nijkamp, P. (2011). *Smart Cities in Europe. Journal of Urban Technology*, 18(2), 65–82. https://doi.org/10.1080/10630732.2011.601117

[2] Clyde Zhengdao Li, Zhe Chen, Fan Xue, Xiang T.R. Kong, Bing Xiao, Xulu Lai, Yiyu Zhao, *A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction*, Journal of Cleaner Production, Volume 286, 2021, 125391, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.125391.

[3] Nguyen, T.D.H.N.; Moon, H.; Ahn, Y. *Critical Review of Trends in Modular Integrated Construction Research with a Focus on Sustainability*. Sustainability 2022, 14, 12282. https://doi.org/10.3390/su141912282

[4] Kineber, A. F. (2024). *Identifying the Internet of Things (IoT) implementation benefits for sustainable construction project.* HBRC Journal, 20(1), 700–766. https://doi.org/10.1080/16874048.2024.2369462

[5] Parracho, D.F.R.; Nour El-Din, M.; Esmaeili, I.; Freitas, S.S.; Rodrigues, L.; Poças Martins, J.; Corvacho, H.; Delgado, J.M.P.Q.; Guimarães, *A.S. Modular Construction in the Digital Age: A Systematic Review on Smart and Sustainable Innovations*. Buildings 2025, 15, 765. https://doi.org/10.3390/buildings15050765

Bibliography

Caragliu, A., Del Bo, C., & Nijkamp, P. (2011). *Smart Cities in Europe. Journal of Urban Technology*, 18(2), 65–82. https://doi.org/10.1080/10630732.2011.601117

Clyde Zhengdao Li, Zhe Chen, Fan Xue, Xiang T.R. Kong, Bing Xiao, Xulu Lai, Yiyu Zhao, *A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction*, Journal of Cleaner Production, Volume 286, 2021, 125391, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.125391.

Nguyen, T.D.H.N.; Moon, H.; Ahn, Y. *Critical Review of Trends in Modular Integrated Construction Research with a Focus on Sustainability*. Sustainability 2022, 14, 12282. https://doi.org/10.3390/su141912282

Kineber, A. F. (2024). *Identifying the Internet of Things (IoT) implementation benefits for sustainable construction project.* HBRC Journal, 20(1), 700–766. https://doi.org/10.1080/16874048.2024.2369462

Parracho, D.F.R.; Nour El-Din, M.; Esmaeili, I.; Freitas, S.S.; Rodrigues, L.; Poças Martins, J.; Corvacho, H.; Delgado, J.M.P.Q.; Guimarães, *A.S. Modular Construction in the Digital Age: A Systematic Review on Smart and Sustainable Innovations*. Buildings 2025, 15, 765. https://doi.org/10.3390/buildings15050765

Boris Ceranic, John Beardmore, Adrian Cox, *Rapid deployment modular building solutions and climatic adaptability: Case based study of a novel approach to "thermal capacity on demand"*, Energy and Buildings, Volume 167, 2018, Pages 124-135, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2018.01.044

Chichernea, Virgil. (2011). *THE ROLE OF COLLABORATIVE SOFTWARE AND DECISION SUPPORT SYSTEMS IN THE SMARTER CITIES*. Romanian Economic Business Review. 5. 45-51.

Chichernea, V. (2015). *Smart cities communities and smart ICT platform.* Journal of Information Systems & Operations Management, 9(1), 26–36, ISSN 1843-4711

Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Pichler-Milanović, N., & Meijers, E. (2007). *Smart cities: Ranking of European medium-sized cities (Report)*. Vienna University of Technology.

Ginigaddara, T., Dissanayake, R., & Jayasundara, J. (2023). *Resilience and performance of prefabricated modular structures in post-disaster housing: A critical review*. European Journal of Structural Engineering (PDF).

Harrison, C., & Donnelly, I. A. (2011). *A theory of smart cities.* Proceedings of the 55th Annual Meeting of the International Society for the Systems Sciences.

International Organization for Standardization. (2018). ISO 37120:2018—Sustainable cities and communities: Indicators for city services and quality of life (Standard).

International Telecommunication Union. (2017). Collection methodology for key performance indicators for smart sustainable cities (U4SSC Report).

National Institute of Standards and Technology. (2022). Smart Cities and Communities: A Key Performance Indicators Framework (NIST publication page).

United Nations Office for Disaster Risk Reduction. (2015). Sendai Framework for Disaster Risk Reduction 2015–2030 (UN framework).

Nicolae Mihoci, Prefabricated, foldable and transportable construction. Romanian Patent RO 106900 B1.

AN EXPERIMENTAL AGENT-BASED CITY SIMULATION: PERSONALITY-DRIVEN ECONOMIC BEHAVIOR AND STABILITY OUTCOMES

Bogdan-Gabriel GHEORGHE[1]

Abstract

This paper presents an agent-based economic simulation in a city-builder environment in which citizens act as autonomous agents driven by personality traits rather than direct player control. Each agent makes decisions regarding work, consumption, and recreation based on internal needs and trait-dependent functions. Workplaces consume and produce resources, while a market regulates prices dynamically through supply-demand interactions. To investigate how behavioral profiles shape economic outcomes, two contrasting population scenarios were evaluated: a Greedy City, dominated by agents with greedy personalities who prioritize personal wealth, and a Diligent City, where agents prioritize filling positions that are in demand even if they have lower salaries. Results show that personality distributions have significant effects on economic stability, production efficiency, and price volatility. The Greedy City produced erratic output patterns, recurrent input shortages, and unstable market prices, whereas the Diligent City maintained consistent production chains, higher overall output, and stable economic conditions after an initial period of job sorting. These findings indicate that variations in agent personality can influence macro-level behavior in the simulated environment, highlighting the potential value of incorporating behavioral diversity in agent-based economic and game simulations.

Keywords: Agent-Based Modeling, Behavioral Simulation, Personality-Driven Decision Making, City-Building Simulation, Market Simulation, Resource Economics

JEL Classification: C63, D91, C7

1. Introduction

Simulating economic behavior in games and virtual environments has evolved from simple production chains to complex systems involving autonomous agents with motivations and personalities. Classical city-building games such as The Settlers[2] and Banished[3] provide resource management and production chains, but they do not explicitly model individual agent personalities that influence macro-level trends.

[1] Engineer, UNSTPB, Romania, bogdan.gheorghe0711@stud.fils.upb.ro

[2] Blue Byte Software, The Settlers, Ubisoft, 1993, https://www.ubisoft.com/en-us/company/about-us/our-brands/the-settlers

[3] Shining Rock Software, Banished, 2014 , https://shiningrocksoftware.com/game/

The present work introduces an experimental economic simulation in which citizens behave according to personality traits such as greed, diligence, or laziness. These traits determine preferences for work, consumption, recreation, housing and job switching. By coupling personality-based agent models with resource-dependent workplaces and a dynamic market, the simulation examines how individual decisions can aggregate into higher-level economic trends.

The main question is "how do different personality distributions within the population affect production, economic stability, and welfare in a city simulation ?" To answer this question, two controlled scenarios were executed: A highly greedy population and a highly diligent population.

2. Related Work

Agent-based modelling (ABM) has become a central methodology for studying complex socio-economic and ecological systems where global behavior emerges from the interaction of autonomous individuals. Early reviews highlighted that ABM can capture differences between agents, how they interact in space, and their various behaviors, making it especially useful for simulation, where individual decisions shape overall outcomes. Bousquet and Le Page (2004) provide a foundational overview of multi-agent simulations in ecosystem management, showing how decentralized agents interacting with resource flows can produce emergent patterns at the system level [1]. Their analysis argues that ABM can be useful for problems with social and spatial aspects.

A significant portion of ABM research concerns the representation of human decisions. An's (2012) review of human decision modeling in coupled human–natural systems highlights that different ABM models have their own strengths and weaknesses, but real humans will change their thinking method and adapt to the environment therefore a system that can replicate that decision making is far away but it can still be useful if the model it's kept simple[2].

Beyond ecological systems, multi-agent simulation has increasingly been applied to socio-economic behavior. Roozmand et al. (2011) demonstrate that incorporating psychological factors such as personality traits and cultural dimensions leads to more realistic consumer decision models and market behavior [3]. Their findings support the use of personality traits in agent-based environments but also say that even after incorporating them, the data were not sufficiently accurate, further continuing the idea that a personality-based ABM can simulate real-world practices, albeit to a lesser degree of accuracy.

At the methodological level, Müller et al. (2013) introduced the ODD + D protocol as an extension of the widely used ODD (Overview, Design concepts, Details) standard for ABM

descriptions [4]. ODD + D explicitly incorporates decision-making processes, mental states, and behavioral rules.

Land-use and economic ABM research has further emphasized the importance of taking into account social interactions and human decisions Matthews et al. (2007) provide a rigorous analysis of agent-based land-use models, noting that heterogeneity is essential in influencing the dynamics of such systems [5].

Recent work also highlights the challenges inherent in analyzing the outputs of complex ABMs. Lee et al. (2015) argue that ABM results are more challenging and require more time and attention than the ABM itself [6].

Steinbacher et al. (2021) state that ABMs are very flexible and can be adapted to very different problems with different conditions and that ABMs as a whole are a promising avenue for research [7].

Overall, the literature supports the core hypothesis of this paper: that micro-level behavioral heterogeneity, especially personality-driven labor and consumption choices, can systematically shape macro-level outcomes.

2.1. Similar games

“The Settlers” is a game that focuses on production flow optimization and efficient transportation. Its citizens do not have internal states or personalities; they function as fixed units that follow predefined roles within supply chains.

In “Banished”, on the other hand, the emphasis is put on survival, resource hardship, and dynamic population needs, but still treats citizens as interchangeable workers without complex decision-making.

Unlike traditional agent-based city-building simulations, this project investigates how incorporating personality-driven decision-making into an agent-based city simulation influences production dynamics, economic stability and citizen welfare. By encoding personality traits as parameters within all the functions and behavior-tree decision logic, the resource flows and economic dynamics emerge from interactions between predetermined production processes and dynamic agent decision-making. This approach provides a structured representation of agent decision-making that allows individual personality variations to influence economic behavior.

3. System Architecture and Methodology

3.1. Overview

The simulation framework is composed of several interacting subsystems that collectively attempt to reproduce the dynamics of an agent-based urban economy. The citizen subsystem models autonomous agents with personality traits, physiological needs (hunger, fatigue),

financial resources, and job preferences, all of which influence their decisions. The workplace system represents productive buildings that transform input resources into output goods and serve as employment nodes within the economic network. A centralized market subsystem controls the flow of all goods and determines prices dynamically through supply–demand interactions.

The time structure is introduced through a daily cycle mechanism that regulates work schedules, consumption routines, and opportunities for job transitions. Agent behavior is further governed by a behavior tree, enabling agents to evaluate and choose among actions such as working, eating, sleeping, or engaging in non-essential activities. Additionally, a housing subsystem models residential mobility, allowing agents to relocate based on income, proximity to workplaces, and personal satisfaction.

All components are implemented in Unity using C#, employing a modular architecture built around node-based behavior trees and specialized scripts.

3.2. Agents

Each citizen agent is characterized by a set of internal attributes and conditions. These include personality traits (e.g., greedy, diligent, lazy, social), which influence decision-making, basic physiological and social needs (such as hunger, fatigue, recreation, and clothing requirements), which generate periodic demands for consumption, personal money from their salary, used to purchase goods and pay for housing and individualized work preferences, including varying degrees of willingness to switch jobs in response to economic situations.

The current implementation makes use of personality traits through modifiers that affect how workplace or needs calculation occurs for the agent. Greedy agents prioritize personal income and therefore disproportionately favor workplaces offering higher salaries, even when such choices undermine overall production-chain efficiency. In the job-switching evaluation, these agents apply an increased weight of 10% of their greedy stat to the salary component of the utility calculation. In contrast, diligent agents are designed to support systemic stability. They preferentially seek employment in workplaces experiencing input shortages and, independently of external conditions, have a 50% probability each day of evaluating alternative positions with the explicit goal of addressing the largest production bottleneck in the city. This mechanism enables diligent agents to act as stabilizing forces within the simulated economy.

3.3. Workplaces and Production Chains

Each workplace in the simulation is defined by a structured set of parameters. These include the required input resources for production, output goods generated through processing activities, the number of workers needed to achieve full operational capacity, and the salary

offered to potential employees. Workplaces also specify operational time windows defined by start and end hours during which production activities and service provision occur. For social or recreational establishments, such as inns, an additional parameter is the maximum number of customers that can be accommodated simultaneously. Furthermore, each workplace maintains a productivity coefficient that evolves according to the cumulative experience of its workforce, enabling more efficient production as employees gain skill over time.

Within the economic system, workplaces function simultaneously as production nodes, transforming inputs into outputs, and as market actors who engage in the buying of required resources and selling of produced goods. This dual role situates workplaces at the core of both the supply chain and market exchange dynamics.

3.4. Central Market and Price Regulation

All goods produced or consumed within the simulation flow through a centralized market, which functions as the primary exchange mechanism between workplaces and agents. The market tracks, for each resource type, the daily supply, demand and shortage accumulated throughout the simulation cycle. At the end of each day, prices are updated using a supply-demand driven adjustment algorithm designed to reflect scarcity, prevent extreme price shocks, and ensure temporal smoothness.

The pricing function operates in these steps:

The first step is calculating the shortage score of the resources, which is calculated as resource demand divided by supply: $resource.shortage = \frac{resource.demand}{resource.supply}$.

After which the function checks to see if it has to apply the upper bounds, in this case, the upper bounds are 20 times the base price of the resource, it does so by comparing the shortage score of that resource with 20, which results in: $resource.shortage < 20$.

If the above is true and the shortage score is less than 20 then the function calculates the new target price for the resource as the base price multiplied with shortage score: $resource.targetPrice = resource.basePrice * resource.shortage$, if the above it's not true and the shortage is more than 20 then the target price become base price multiplied with 20: $resource.targetPrice = resource.basePrice * 20$ and if both of those are untrue and the demand and supply are both equal to 0 then the target price become the base price: $resource.targetPrice = resource.basePrice$.

Lastly we interpolate and calculate the current price which will be the interpolation between the old price of the resource and the target price with the rate of adjustment controlled by a smoothing factor pre-decided: $resource.price = Mathf.Lerp(resource.price, resource.targetPrice, smoothing)$,

After the update, daily supply and demand values are reset for the next simulation cycle.

This mechanism ensures that rare goods become expensive, abundant goods become inexpensive, and price evolution remains stable and continuous rather than oscillatory. Consequently, dynamic prices influence both production behaviors as workplaces adjust to input scarcity and consumption behavior, since agents evaluate affordability when fulfilling their needs.

3.5. Decision System (Behavior Trees)

Each citizen agent employs a behavior-tree architecture to evaluate and execute actions according to internal needs, personality, and environmental conditions. The decision process follows a priority-based evaluation model:

1. Work participation: Agents determine whether to attend their assigned workplace, conditional on current work hours, energy levels (food and sleep), and personal traits influencing diligence or laziness.
2. Food acquisition: If hunger exceeds a personality-adjusted threshold, the agent initiates a food search. Lazy agents tolerate higher hunger levels before acting, whereas more disciplined personalities intervene earlier.
3. Sleep behavior: Agents decide to rest when energy drops below a trait-dependent threshold. Lazy personalities exhibit increased sleep duration and earlier withdrawal from productive activities.
4. Recreation: If the mood falls below a defined threshold, the agent seeks recreational venues, such as inns to restore it.
5. Job switching: Agents periodically evaluate alternative employment options based on a utility calculation influenced by personality and workplace characteristics

The job-switching mechanism is personality-dependent. Standard agents compare the score of their current workplace with alternatives. The standard score is calculated as follows:

First, the function calculates a weighted dot product between 2 vectors, 1 vector is the citizens traits while the other is the workplace's traits, if C is the vector of citizen traits and W is the vector for the workplace than the sum so far would be : $S = \sum_{i=1}^{8} C_i \; W_i$.

Then it calculates the salary component which is the citizens greed trait value multiplied with salary of the workplace multiplied with 0.01 which results in : $SalaryScore = Citizen.greed * Workplace.salary * 0.01$.

At the end the function adds those two together and then subtracts the distance between the workplace and the citizens house which make the final equation : $Score = S + SalaryScore - DistanceFromHome$. After this is the new score is better than the old score the citizen will change its workplace at the next available time.

Greedy agents assign disproportionately high weight to the salary component, effectively diminishing the relevance of distance or personal affinity. This leads them to cluster around high-paying workplaces, even when doing so destabilizes production chains.

In contrast, diligent agents prioritize economic stability. They mainly move toward workplaces experiencing a significant production bottleneck, that is calculated through a ShortageScore. When this score becomes sufficiently low, indicating an unmet demand for essential inputs, diligent agents have a chance to voluntarily relocate to mitigate the shortage, independent of salary considerations.

4. Experimental Design

4.1. Scenarios

Two experimental scenarios were simulated, each comprising a population of 66 citizen agents interacting within an identical economic and infrastructural environment. The production system consisted of the following workplaces: two farms, one lumber mill, one mine, two toolmakers, one jeweler, one clothmaker, and one textile maker. Each workplace transforms specific input resources into output goods at rates determined by its l characteristics. Input consumption and output production differ across workplaces, reflecting processing efficiencies.

Workplaces also incorporate temporal constraints, operating only during predefined hours, and impose capacity limits on the number of employees that can be assigned simultaneously. In addition, the simulation includes a skill-accumulation mechanism: for every in-game day an agent works at a given workplace, their proficiency in that occupation increases, thereby enhancing the productivity of the workplace through accumulated employee experience. The two scenarios differ exclusively in their population personality composition:

- Scenario A — “Greedy City”: 80% of agents possess greedy traits, 10% are diligent, and the remaining 10% are assigned other personality types.
- Scenario B — “Diligent City”: 80% of agents are diligent, 10% are greedy, and 10% exhibit other behaviors.

4.2. Evaluation metrics

The evaluation framework monitored several quantitative indicators designed to capture both micro-level agent behavior and macro-level economic performance. Specifically, the following metrics were recorded:

- Economic output, measured as the total quantity of goods produced across all workplaces.
- Production stability, measured through the frequency and severity of input shortages within production chains.
- Price volatility, reflecting fluctuations in market prices arising from supply–demand imbalances.

- Citizen welfare, assessed through indicators of food and clothing availability, agent mood states, and sleep adequacy.
- Job switching frequency represents the rate at which agents make transitions between workplaces in response to score evaluations and personality-driven tendencies.

All metrics were logged at the granularity of one in-game day. Data collection spans a 14-day simulation period for each scenario, covering all workplaces and the entire agent population.

5. Results

5.1. Output and Stability

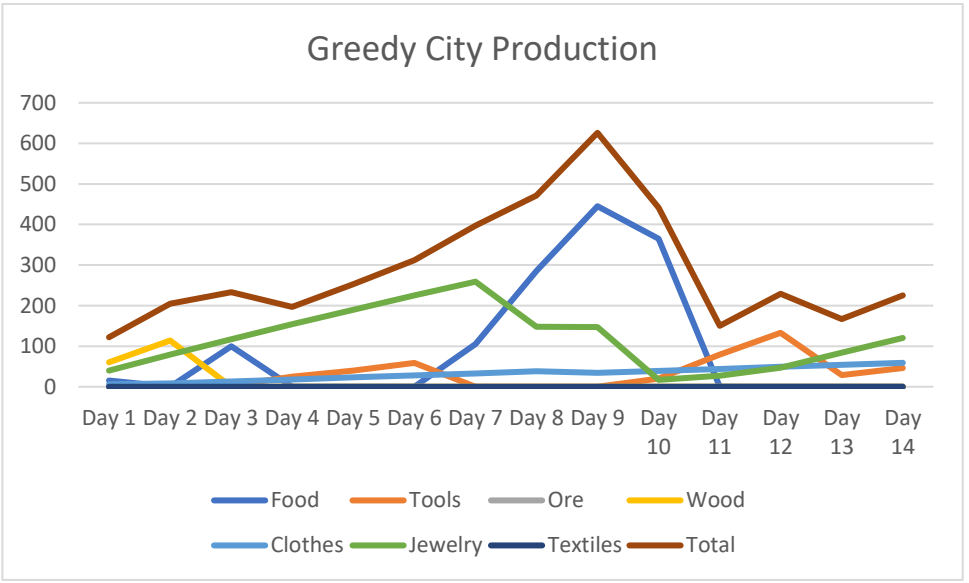


Chart 1. Greedy City Production Chart

Production in the Greedy City exhibited substantial instability, characterized by recurrent input shortages and frequent disruptions in output continuity. As prices fluctuated due to the agents' collective behavior, greedy workers tended to abandon their current positions whenever the market value of another good became more attractive. This led to rapid switching toward workplaces associated with temporarily higher-priced outputs. Such behavior created labor imbalances, amplifying shortages further destabilizing the production chain.

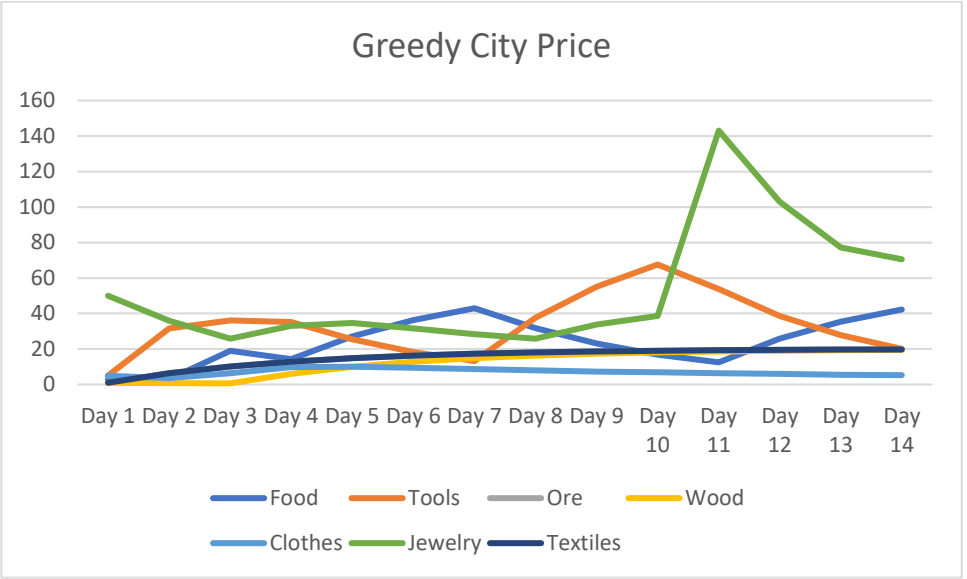


Chart 2. Greedy City Price Chart

Price dynamics in the Greedy City were similarly unstable, largely as a consequence of the irregular labor allocation patterns observed across workplaces. Places that failed to generate high wages suffered from understaffing, which in turn limited their production capacity. Workers employed in these low-income workplaces had reduced purchasing power and were therefore unable to meet even basic consumption needs. This reduction in effective demand further decreased the market value of the goods produced in those places. The resulting feedback loop, low wages leading to low demand, which then leads to even lower incentives for workers to join or remain in those industries, was especially important for essential goods such as clothing, textiles, and wood. These goods, while fundamental for agent survival, experienced reduced production and declining prices because greedy agents consistently moved towards more profitable sectors. This dynamic significantly amplified economic instability and weakened the overall production system.

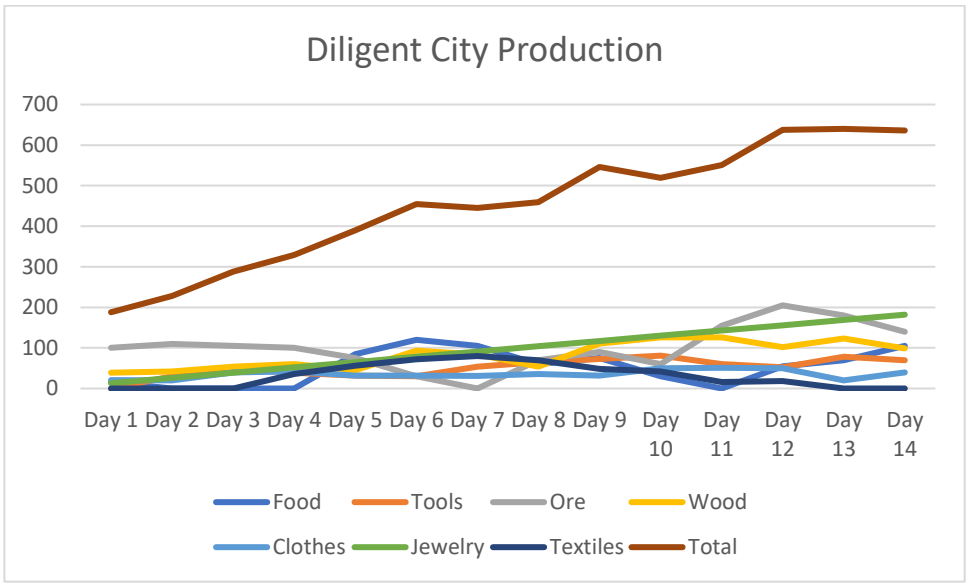


Chart 3. Diligent City Production Chart

In contrast to the Greedy City, the Diligent City demonstrated a steady and consistently increasing level of production across all goods, accompanied by only minimal shortages as the simulation progressed. The stable labor allocation characteristic of diligent agents, who reliably occupy essential positions within the production chain, enabled workplaces to maintain continuous inputs and sustain good output levels. This resulted in a more resilient and efficient economic system compared to the volatile dynamics observed in the Greedy scenario.

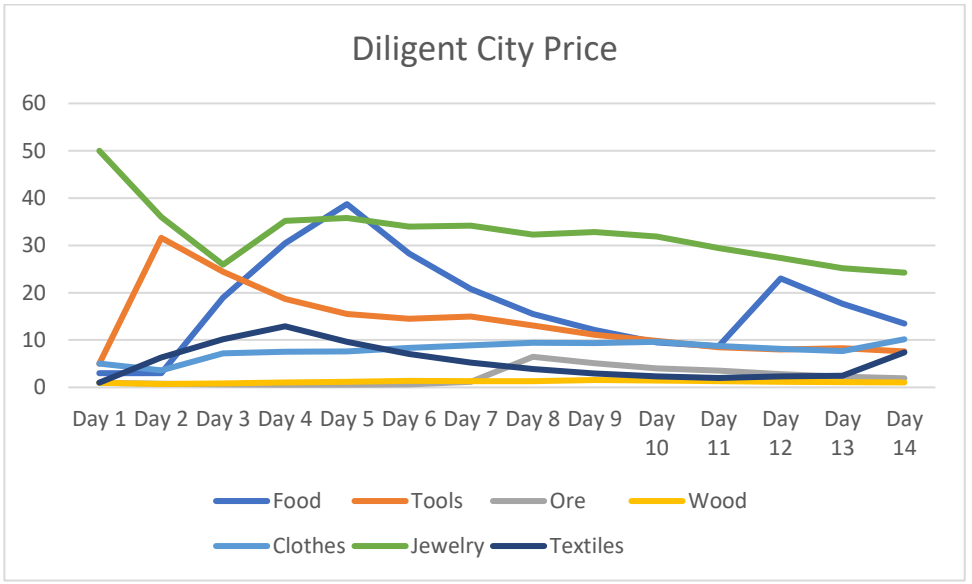


Chart 4. Diligent City Price Chart

In the Diligent City, during the initial days the price levels exhibited a temporary instability, reflecting the supply fluctuations caused by erratic labor distribution. However, as certain shortages were gradually alleviated and production stabilized in workplaces, market prices began to converge toward their respective base values. This downward adjustment improved the affordability of essential goods and increased accessibility for the agent population, partially mitigating the economic disruption observed at the start of the scenario.

5.2. Welfare and Consumption

The two scenarios also produced different patterns in citizen welfare and daily living conditions. Greedy agents exhibited several indicators of reduced and unstable well-being. Their consumption behavior was irregular, resulting in:

- Lower and highly inconsistent food intake, driven by fluctuating income and frequent job instability
- Irregular access to clothing, reflecting reduced purchasing power in low-wage periods
- Elevated purchases of jewelry, a consequence of high production output and strong demand, which temporarily increased disposable income
- Frequent relocation between houses, arising from constant job changes and shifting economic circumstances.

In contrast, diligent agents maintained significantly more stable life patterns due to their consistent employment and income. This manifested in:

- More regular and reliable eating and sleeping routines.
- Higher overall mood, driven by reduced unmet needs.
- Fewer days without access to food or clothing reflecting better alignment between income and consumption requirements.
- Greater productivity, as agents remained in the same workplace for longer periods and accumulated experience, thereby enhancing workplace output.

5.3. Job Switching Frequency

In the Greedy City, persistent shortages caused sharp fluctuations in both market prices and workplace salaries. As wages in shortage-affected industries increased, greedy agents whose decision-making heavily prioritizes income frequently abandoned their current jobs in favor of newly profitable opportunities. This behavior produced a highly volatile labor market, with an average of approximately 23 job switches per in-game day. The continual

reallocation of labor further amplified production instability, creating a self-reinforcing cycle of shortages, wage spikes, and additional job switching.

In contrast, the Diligent City exhibited a more stable labor environment. As diligent agents consistently filled essential positions, production bottlenecks were gradually resolved, leading to more balanced supply levels across resource types. With shortages alleviated, workplace salaries and prices tended to converge toward stable values, reducing the economic incentive for workers to relocate. As a result, the simulation recorded approximately 11 job transitions per day, roughly half the rate observed in the Greedy City. This stability further contributed to sustained productivity and more reliable economic performance.

6. Discussion

The results support the main hypothesis: the distribution of personality traits in the population significantly affects the overall economic behavior observed in the simulation.

The Greedy scenario displayed a pattern of agents individually optimizing for short-term salary gains but collectively undermining the broader economy. Specifically, greedy agents:

- Overstaffing high-salary workplaces (e.g., Jeweler, Toolmaker)
- Ignoring essential basic inputs (farms, mines, textiles)
- Causing price surges and production collapse

Conversely, the Diligent population exhibited behavior aligned with collective welfare and long-term system stability. These agents:

- Self-organized into efficient production chains
- Maintained stable resource flow
- Achieved higher aggregate welfare metrics, including food availability, clothing access, and mood stability.

Together, these findings suggest that differences in agents' personality traits can meaningfully influence overall economic behavior.

7. Limitations

The current data represents a single 14-day cycle simulation, while multiple simulations were run to ensure similar and consistent results across, the current data was recorded from just one of them. Which means that the conclusions are only orientational and are dependent on the initial conditions of each simulation.

The current implementation presents several limitations that constrain the generalizability and long-term applicability of the findings. First, the simulation does not yet incorporate demographic dynamics such as birth, death, aging, or migration, limiting its ability to represent population evolution over extended periods. Second, the experimental design evaluates only two primary personality distributions, which restricts the exploration of more diverse behavioral or mixed-trait societies.

Although prices adjust through an internal market mechanism, the system does not currently model taxation, government policy, or external trade, all of which play critical roles in real-world economic environments. In addition, workplaces operate with fixed production rules and do not yet adapt outputs in response to market conditions, preventing the observation of more realistic firm-level optimization behaviors.

Practical constraints also influenced system complexity. Due to development time limitations and the experimental nature of the application, several advanced features were excluded from the current version. Furthermore, the simulation engine is not yet optimized for large-scale, long-duration scenarios, making it computationally challenging to run simulations with very large populations or extended time horizons.

These limitations highlight areas for future refinement and expansion in order to support more robust and realistic economic modeling.

8. Conclusions

This project demonstrates that integrating personality traits into an agent-based economic simulations can produce measurable, interpretable variations in macro-level behavior within a controlled experimental setting. In the presented scenarios, populations dominated by greedy agents behave similarly to unstable boom–bust economies, characterized by labor volatility, production bottlenecks, and highly fluctuating prices. In contrast, populations dominated by diligent agents show greater self-organization, more stable production chains, and higher general welfare.

While the model is not intended as a predictive economic tool, these results suggest that psychological diversity at the agent level can meaningfully shape economic structures in simulation-based environments. This has potential implications for both game development and exploratory research in agent-based economic modeling.

Future work will expand the model's scope by improving support for large-scale, long-duration simulations and introducing additional personality types with more depth. Planned improvements include a more complex behavior tree that will enable more nuanced decision-making and allow agents and workplaces to sell surplus goods such as jewelry into broader markets.

References

[1] Bousquet, F. and Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecological modelling, 176(3-4), pp.313-332.

[2] An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological modelling, 229, pp.25-36.

[3] Roozmand, O., Ghasem-Aghaee, N., Hofstede, G.J., Nematbakhsh, M.A., Baraani, A. and Verwaart, T., 2011. Agent-based modeling of consumer decision making process based on power distance and personality. Knowledge-Based Systems, 24(7), pp.1075-1095.

[4] Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. and Schwarz, N., 2013. Describing human decisions in agent-based models–ODD+ D, an extension of the ODD protocol. Environmental Modelling & Software, 48, pp.37-48.

[5] Matthews, R.B., Gilbert, N.G., Roach, A., Polhill, J.G. and Gotts, N.M., 2007. Agent-based land-use models: a review of applications. Landscape Ecology, 22(10), pp.1447-1459.

[6] Lee, J.S., Filatova, T., Ligmann-Zielinska, A., Hassani-Mahmooei, B., Stonedahl, F., Lorscheid, I., Voinov, A., Polhill, J.G., Sun, Z. and Parker, D.C., 2015. The complexities of agent-based modeling output analysis. Journal of Artificial Societies and Social Simulation, 18(4).

[7] Steinbacher, M., Raddant, M., Karimi, F., Camacho Cuena, E., Alfarano, S., Iori, G. and Lux, T., Advances in the agent-based modeling of economic and social behavior. SN Bus Econ 1, 99 (2021) [online]

Bibliography

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological modelling, 229, pp.25-36.

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences, 99(suppl_3), pp.7280-7287.

Bousquet, F. and Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecological modelling, 176(3-4), pp.313-332.

Chang, X., Liu, L., Liu, Z. and Chen, W., 2013. Method of multi-agent system for simulating land-use decision-making behavior of farmer households. Transactions of the Chinese Society of Agricultural Engineering, 29(14), pp.227-237.

Dumitrescu, C., Radu, V., Gheorghe, R., Tăbîrcă, A.I., Ștefan, M.C. and Manea, L., 2024. Crowd panic behavior simulation using multi-agent modeling. Electronics, 13(18), p.3622.

Lee, J.S., Filatova, T., Ligmann-Zielinska, A., Hassani-Mahmooei, B., Stonedahl, F., Lorscheid, I., Voinov, A., Polhill, J.G., Sun, Z. and Parker, D.C., 2015. The complexities of agent-based modeling output analysis. Journal of Artificial Societies and Social Simulation, 18(4).

Leoneti, A.B., Bañares-Alcántara, R., Pires, E.C. and de Oliveira, S.V.W.B., 2022. A multi-criteria and multi-agent framework for supporting complex decision-making processes. Group Decision and Negotiation, 31(5), pp.1025-1050.

Matthews, R.B., Gilbert, N.G., Roach, A., Polhill, J.G. and Gotts, N.M., 2007. Agent-based land-use models: a review of applications. Landscape Ecology, 22(10), pp.1447-1459.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. and Schwarz, N., 2013. Describing human decisions in agent-based models–ODD+ D, an extension of the ODD protocol. Environmental Modelling & Software, 48, pp.37-48.

Pilla, V., Patel, N.V. and Khan, T., 2012. Multi-agent simulation of business processes: a theoretical model to manage and report carbon footprint in an emergent organisation. International Journal of Business Information Systems, 9(4), pp.435-450.

Roozmand, O., Ghasem-Aghaee, N., Hofstede, G.J., Nematbakhsh, M.A., Baraani, A. and Verwaart, T., 2011. Agent-based modeling of consumer decision making process based on power distance and personality. Knowledge-Based Systems, 24(7), pp.1075-1095.

Steinbacher, M., Raddant, M., Karimi, F., Camacho Cuena, E., Alfarano, S., Iori, G. and Lux, T., Advances in the agent-based modeling of economic and social behavior. SN Bus Econ 1, 99 (2021) [online]

INTELLIGENCE-ENABLED SUSTAINABLE MARKETING IN SDG-DRIVEN MARKETS: INTEGRATING DIGITAL TRANSFORMATION, COMPETITIVE INTELLIGENCE, AND ORGANIZATIONAL CONSCIOUSNESS

Cezara M. GIUGULA[1]
Daniel G. DINU[2]

Abstract

The purpose of this paper is to reconceptualize sustainable marketing in the context of SDG-driven markets by integrating sustainable marketing theory, digital transformation (DT), and Competitive Intelligence (CI). The paper addresses the limitations of predominantly normative sustainability approaches by advancing a strategic, intelligence-based perspective on how firms navigate sustainability under conditions of uncertainty and digital acceleration.

This study adopts a conceptual and theory-building approach. Drawing on literature from sustainable marketing, Competitive Intelligence, digital transformation, and governance, the paper develops an integrative conceptual framework grounded in a societal evolution lens distinguishing between information, knowledge, and organizational consciousness.

The paper proposes that sustainable marketing effectiveness does not arise directly from digital capabilities alone, but from their mediation through Competitive Intelligence and their governance through strategic autonomy. This interaction produces organizational consciousness – defined as system-level awareness of the economic, social, and environmental consequences of market action – enabling durable competitive advantage in SDG-driven markets.

The paper contributes to sustainable marketing theory by positioning Competitive Intelligence as the central mediating mechanism between digital transformation and sustainability outcomes. It introduces organizational consciousness as a governance-level strategic outcome and reframes marketing as an intelligence-enabled coordination function within sustainability governance systems.

The framework offers guidance for managers seeking to embed intelligence capabilities into sustainable marketing strategies and to align digital infrastructures with long-term sustainability objectives.

By linking intelligence, governance, and sustainability, the paper highlights how marketing can contribute to more accountable, transparent, and socially responsive market systems aligned with the Sustainable Development Goals.

[1] MSc, King's College London, UK, cezara.m.giugula@gmail.com
[2] PhD, Fellow, EuroMed Academy, Cyprus, daniel.dinu90@gmail.com

Keywords: Digital transformation; Competitive Intelligence; Sustainable marketing; Organizational consciousness; SDG-driven markets; Sustainability governance
JEL Classification: D91, L86, M31, Z32

1. Introduction

Organizations increasingly operate under heightened pressure to align market strategies with global sustainability imperatives. The United Nations Sustainable Development Goals (SDGs) have emerged as a dominant institutional framework shaping expectations regarding corporate responsibility, transparency, and long-term value creation across industries [1]. For marketing functions, this shift represents more than a normative adjustment; it challenges the foundational logic through which value is defined, communicated, and governed in markets characterized by growing social, environmental, and regulatory complexity.

Sustainable marketing has developed as a response to these pressures by extending traditional market orientation to include environmental and social considerations alongside economic objectives [2]. Research suggests that sustainability-oriented marketing practices can enhance brand reputation, stakeholder trust, and organizational legitimacy, particularly in contexts marked by regulatory scrutiny and societal visibility [3]. However, despite its normative appeal, sustainable marketing scholarship has been criticized for offering limited insight into how firms can strategically navigate sustainability under conditions of uncertainty, institutional volatility, and competitive imitation [4]. Much of the literature emphasizes *what* firms should do, while paying less attention to *how* they can anticipate, interpret, and respond to evolving sustainability demands.

At the same time, digital transformation has profoundly reshaped marketing practice. The widespread adoption of data analytics, artificial intelligence, and platform-based infrastructures has expanded firms' capacity to collect market information, personalize offerings, and optimize performance in real time [5]. While these technologies enhance efficiency and scale, they also tend to privilege short-term performance metrics and predictive accuracy, often reinforcing extractive or growth-centric logics that sit uneasily with the long-term, systemic orientation implied by the SDGs [6]. As a result, digital marketing systems may exacerbate tensions between sustainability commitments and market execution rather than resolve them.

This tension foregrounds the strategic relevance of Competitive Intelligence (CI). Traditionally understood as the systematic collection and analysis of information about competitors and markets, CI has evolved into a broader strategic capability concerned with environmental scanning, sensemaking, and anticipatory decision-making [7]. In sustainability contexts, CI offers a mechanism through which firms can move beyond reactive compliance and toward proactive alignment with emerging stakeholder expectations, regulatory trajectories, and societal norms. Yet, despite its relevance, CI remains under-theorized within sustainable marketing research, and its role in mediating

between digital transformation and sustainability outcomes has received limited scholarly attention.

The convergence of sustainability imperatives, digital transformation, and intelligence capabilities suggests the emergence of a new marketing paradigm in SDG-driven markets. To conceptualize this shift, this paper adopts a societal evolution lens that distinguishes between information, knowledge, and organizational consciousness [8]. While information- and knowledge-based perspectives emphasize data accumulation and learning, SDG-driven markets increasingly require organizations to develop second-order awareness of the systemic economic, social, and environmental consequences of market actions [9]. In this paper, such organizational consciousness is framed not as an individual psychological state, but as a governance-related capability that emerges through sustained intelligence processes.

Against this background, the purpose of this conceptual paper is to integrate sustainable marketing, digital transformation, and Competitive Intelligence into a unified framework suitable for SDG-driven markets. Specifically, the paper advances three core contributions. First, it reconceptualizes sustainable marketing as an intelligence-enabled governance capability rather than a predominantly normative orientation. Second, it positions Competitive Intelligence as the mediating mechanism through which digital transformation translates into sustainability-aligned marketing outcomes. Third, it introduces organizational consciousness as a higher-order strategic outcome that reflects firms' capacity to internalize systemic consequences and align market behavior with societal goals.

By articulating a set of theoretically grounded propositions and an integrative conceptual framework, this paper responds to calls for more strategic, system-level approaches to sustainable marketing. In doing so, it contributes to ongoing debates on sustainability, digital transformation, and intelligence-based strategy, while offering a foundation for future empirical research on marketing in SDG-oriented institutional environments.

Key Contributions

This paper offers three main contributions to the literature on sustainable marketing, Digital Transformation, and Competitive Intelligence in the context of SDG-driven markets:

1. Reconceptualization of Sustainable Marketing as an Intelligence-Enabled Governance Capability

The study reframes sustainable marketing from a predominantly normative or ethical orientation toward a strategic governance capability grounded in intelligence processes. Rather than treating sustainability as a static commitment or reputational objective, the paper conceptualizes sustainable marketing as a coordinated decision-making system that integrates digital infrastructures, intelligence analysis, and institutional awareness. This perspective advances the literature by positioning marketing as an anticipatory governance

mechanism capable of aligning corporate strategy with evolving sustainability expectations in complex regulatory and societal environments.

2. Identification of Competitive Intelligence as the Mediating Mechanism Between Digital Transformation and Sustainability Outcomes

The framework introduced in the paper establishes Competitive Intelligence (CI) as the missing operational link connecting digital transformation to sustainability-aligned marketing strategies. While digital technologies enhance data collection and analytical capabilities, the study argues that these capabilities translate into sustainable outcomes only when mediated by CI processes that interpret signals, anticipate regulatory trajectories, and contextualize market dynamics. This contribution extends digital transformation research by emphasizing interpretive mediation and strategic foresight rather than technological determinism.

3. Introduction of Organizational Consciousness as a Higher-Order Strategic Outcome in Marketing Systems

The paper introduces the concept of **organizational consciousness** as a system-level outcome emerging from sustained intelligence capabilities. Organizational consciousness is defined as second-order awareness of the economic, social, and environmental consequences of market actions. By integrating insights from sensemaking theory and sustainability governance, the study proposes that intelligence-enabled marketing systems can evolve beyond knowledge accumulation toward reflexive and system-aware strategic decision-making. This conceptualization expands marketing theory by linking intelligence capabilities to long-term legitimacy, trust, and durable competitive advantage in SDG-driven markets.

Literature Review

This paper integrates three complementary theoretical domains –sustainable marketing, digital transformation, and Competitive Intelligence (CI) – to reconceptualize marketing strategy in SDG-driven markets. To structure this integration, the section adopts a societal evolution lens that distinguishes between information, knowledge, and organizational consciousness. This lens provides a coherent foundation for understanding how marketing functions evolve under conditions of sustainability governance, technological intensification, and institutional complexity.

1.1. Sustainable Marketing in SDG-Driven Markets

Sustainable marketing extends traditional marketing logic by embedding environmental and social considerations into value creation, communication, and exchange processes. Drawing on stakeholder theory and corporate social responsibility (CSR), sustainable marketing emphasizes long-term value for multiple stakeholders rather than short-term transactional efficiency [2] [10]. Empirical research suggests that sustainability-oriented marketing practices can enhance brand reputation, stakeholder trust, and organizational legitimacy, particularly in contexts characterized by high regulatory scrutiny and societal visibility [3].

Despite these contributions, the sustainable marketing literature remains largely normative. Much of the research focuses on ethical intent, alignment with sustainability principles, or post hoc performance outcomes, offering limited insight into how firms strategically navigate sustainability-related uncertainty [4]. In SDG-driven markets, sustainability expectations are dynamic and contested, shaped by evolving regulatory regimes, stakeholder activism, and competitive imitation. These conditions expose the limitations of sustainability approaches that rely on static standards or reactive compliance. Consequently, sustainable marketing increasingly requires anticipatory capabilities that enable firms to sense, interpret, and respond to emerging societal and institutional demands.

1.2. Digital Transformation and the Limits of Data-Centric Marketing

Digital transformation has fundamentally reshaped marketing practice through the widespread adoption of data analytics, artificial intelligence, and platform-based infrastructures. Digital marketing systems enable firms to collect vast quantities of market data, automate customer engagement, and optimize performance in real time [5]. These capabilities have been associated with improvements in efficiency, scalability, and personalization across industries.

However, digital transformation also introduces structural tensions with sustainability objectives. Data-driven marketing systems are typically optimized for short-term metrics such as engagement, conversion, and growth, which may reinforce extractive or efficiency-centric logics that conflict with long-term social and environmental goals [6]. Moreover,

increasing reliance on external platforms and proprietary algorithms raises concerns related to transparency, accountability, and data governance [11]. These tensions suggest that digital transformation, while necessary, is insufficient on its own to support sustainable marketing in SDG-driven markets.

1.3. Competitive Intelligence as a Dynamic Capability

Competitive Intelligence provides a theoretical bridge between sustainable marketing and digital transformation. Traditionally defined as the systematic collection and analysis of information about competitors and markets, CI has evolved into a broader strategic function concerned with environmental scanning, sensemaking, and anticipatory decision-making [7]. Contemporary CI scholarship emphasizes the role of intelligence in reducing uncertainty and enabling proactive strategic responses in complex and volatile environments.

1.4. From Knowledge to Organizational Consciousness

To integrate these domains, this paper adopts a societal evolution lens that distinguishes between information, knowledge, and organizational consciousness. In an information-oriented logic, marketing focuses on data dissemination and communication efficiency. In a knowledge-oriented logic, emphasis shifts toward learning, expertise, and market orientation [12]. However, SDG-driven markets increasingly demand a further evolution toward organizational consciousness.

In this paper, organizational consciousness is conceptualized as second-order organizational awareness of the systemic economic, social, and environmental consequences of market actions. Consciousness does not replace knowledge; rather, it builds upon it by integrating ethical reflexivity, system-level perspective, and long-term consequence evaluation into strategic decision-making [9]. This framing avoids psychological interpretations and instead positions consciousness as a governance-related capability emerging from sustained intelligence processes.

Competitive Intelligence plays a central role in this transition by integrating heterogeneous sources of information – market data, regulatory signals, stakeholder expectations, and societal trends – into coherent strategic interpretations. Through CI, marketing functions move beyond knowledge accumulation toward a more reflexive, accountable, and sustainability-aligned orientation.

1.5. Strategic Autonomy and Sustainability Governance

Finally, the theoretical foundation recognizes strategic autonomy in digital infrastructure as a critical contextual condition. As firms become increasingly dependent on digital platforms and external data ecosystems, their ability to govern intelligence processes and align them with sustainability objectives may be constrained [11]. Strategic autonomy – often

discussed in terms of digital sovereignty – refers to the capacity of firms to control data, technologies, and analytical systems in accordance with regulatory and societal expectations [13].

In SDG-driven markets, strategic autonomy enhances firms' ability to ensure transparency, accountability, and ethical alignment in marketing practices. It also conditions the effectiveness of Competitive Intelligence by shaping how data is accessed, interpreted, and deployed. As such, strategic autonomy constitutes an essential element of the governance environment within which intelligence-enabled sustainable marketing operates.

2. Model Propositions and Conceptual Framework

Building on the theoretical foundations of sustainable marketing, digital transformation, and Competitive Intelligence (CI), this section advances a set of formal propositions and introduces the conceptual framework that structures the paper's argument. The propositions articulate how intelligence capabilities mediate and condition the relationship between sustainability imperatives and digital marketing systems in SDG-driven markets.

2.1 Sustainable Marketing and Competitive Intelligence

Sustainable marketing extends traditional market orientation by incorporating environmental and social considerations into value creation and exchange processes [2] [10]. However, much of the existing literature conceptualizes sustainability primarily as a normative or ethical orientation, offering limited guidance on how firms can anticipate and respond to evolving sustainability expectations under conditions of uncertainty and institutional change [4].

In SDG-driven markets, sustainability requirements are dynamic, shaped by regulatory evolution, stakeholder activism, and competitive imitation [1]. Competitive Intelligence provides the strategic mechanism through which sustainable marketing can move from reactive compliance toward anticipatory alignment. By systematically scanning and interpreting signals from markets, competitors, regulators, and stakeholders, CI enables firms to identify emerging sustainability-related trends before they materialize as formal constraints or reputational risks [7].

Proposition 1 (P1): *Firms that integrate Competitive Intelligence into sustainable marketing practices exhibit higher anticipatory alignment with SDG-related stakeholder and regulatory expectations than firms that rely on reactive sustainability approaches*.

2.2 Digital Transformation and the Mediating Role of Competitive Intelligence

Digital transformation has reshaped marketing practice through the widespread adoption of data analytics, artificial intelligence, and platform-based infrastructures [5]. These technologies expand firms' capacity to collect and process market data, enabling real-time optimization of customer engagement and performance outcomes. However, digital transformation alone does not ensure alignment with long-term sustainability objectives.

Data-driven marketing systems are often optimized for short-term efficiency and growth metrics, reinforcing extractive or efficiency-centric logics that may conflict with sustainability goals [6]. Competitive Intelligence mediates this relationship by introducing interpretive judgment, contextual awareness, and temporal depth into digitally enabled marketing systems. Through CI, firms translate raw digital data into strategic foresight, distinguishing transient market signals from structurally significant sustainability trends.

Proposition 2 (P2): *Digital transformation enhances sustainable marketing effectiveness only when mediated by Competitive Intelligence capabilities that translate data into forward-looking, system-level insight*.

2.3 Competitive Intelligence and Organizational Consciousness

Beyond its instrumental role, Competitive Intelligence contributes to the development of organizational consciousness. In this paper, consciousness is conceptualized as second-order organizational awareness of the systemic economic, social, and environmental consequences of market actions. This conception builds on sensemaking theory, which emphasizes how organizations construct meaning under conditions of complexity and ambiguity [9].

CI facilitates this transition by integrating heterogeneous sources of information – market data, regulatory signals, stakeholder discourse, and societal trends – into coherent strategic interpretations. As intelligence capabilities mature, marketing functions increasingly operate with reflexivity regarding their broader societal impact, aligning value propositions with SDG objectives rather than narrowly defined market metrics.

Proposition 3 (P3): *Higher levels of Competitive Intelligence capability are positively associated with the development of organizational consciousness in marketing, reflected in greater systemic awareness and reflexivity in strategic decision-making*.

2.4 Strategic Autonomy as a Moderating Condition

The effectiveness of intelligence-driven sustainable marketing is conditioned by firms' degree of strategic autonomy in digital infrastructure. As marketing becomes increasingly dependent on external platforms, proprietary algorithms, and data ecosystems, firms may face constraints on data governance, transparency, and regulatory compliance [11].

Strategic autonomy – often discussed in terms of digital sovereignty – enhances firms' ability to govern intelligence processes and align them with sustainability objectives [13]. Firms with greater control over their digital infrastructures are better positioned to ensure accountability, adapt to regulatory change, and maintain stakeholder trust. Strategic autonomy thus moderates the relationship between CI and sustainable marketing effectiveness.

Proposition 4 (P4): *Strategic autonomy in digital infrastructure strengthens the positive relationship between Competitive Intelligence and sustainable marketing effectiveness.*

2.5 Intelligence-Driven Sustainable Marketing and Competitive Advantage

Sustainable marketing initiatives can generate reputational benefits, stakeholder trust, and organizational legitimacy [3]. However, these benefits are fragile when sustainability claims lack coherence, credibility, or consistency with organizational practice. Competitive Intelligence enhances the robustness of sustainability outcomes by enabling continuous verification, monitoring, and adaptation to evolving societal and regulatory standards.

From a resource-based and dynamic capabilities perspective, intelligence-driven sustainable marketing constitutes a difficult-to-imitate strategic capability [14] [15]. Organizational routines for sensing and interpreting sustainability-related change become embedded within marketing governance structures, contributing to long-term resilience and durable competitive advantage.

Proposition 5 (P5): *Firms that deploy Competitive Intelligence as a core component of sustainable marketing strategy are more likely to achieve durable competitive advantage through enhanced credibility, trust, and regulatory legitimacy*.

2.6 Conceptual Framework

Figure 1 presents the intelligence-enabled sustainable marketing framework developed in this paper. The framework integrates digital transformation, competitive intelligence, strategic autonomy, and organizational consciousness to explain how sustainable marketing effectiveness is generated in SDG-driven markets. Competitive Intelligence is positioned as the central mediating capability through which digital transformation translates into sustainability-aligned marketing outcomes, while strategic autonomy in digital infrastructure functions as a moderating governance condition shaping the effectiveness of intelligence deployment.

The framework conceptualises sustainable marketing as an Intelligence–Governance–Consciousness mechanism rather than a static or descriptive model. Digital transformation constitutes a necessary informational and infrastructural condition, but does not, in itself, generate sustainability-aligned outcomes. Competitive Intelligence mediates this relationship by transforming digitally generated data into anticipatory, interpretive, and strategically actionable insight regarding stakeholder expectations, regulatory trajectories, and systemic sustainability risks [7] [15]. Strategic autonomy conditions this process by shaping the degree of control firms retain over data governance, transparency, and accountability [11] [13].

Through the interaction of mediated intelligence and governance conditions, organizational consciousness emerges as a higher-order strategic outcome. Organizational consciousness is defined as second-order, system-level awareness of the economic, social, and environmental consequences of market actions, extending sensemaking beyond knowledge accumulation toward reflexive sustainability governance [9]. This mechanism underpins sustainable marketing effectiveness by enabling anticipatory alignment with SDG-related expectations and the development of durable competitive advantage grounded in legitimacy, trust, and regulatory coherence [14] [3].

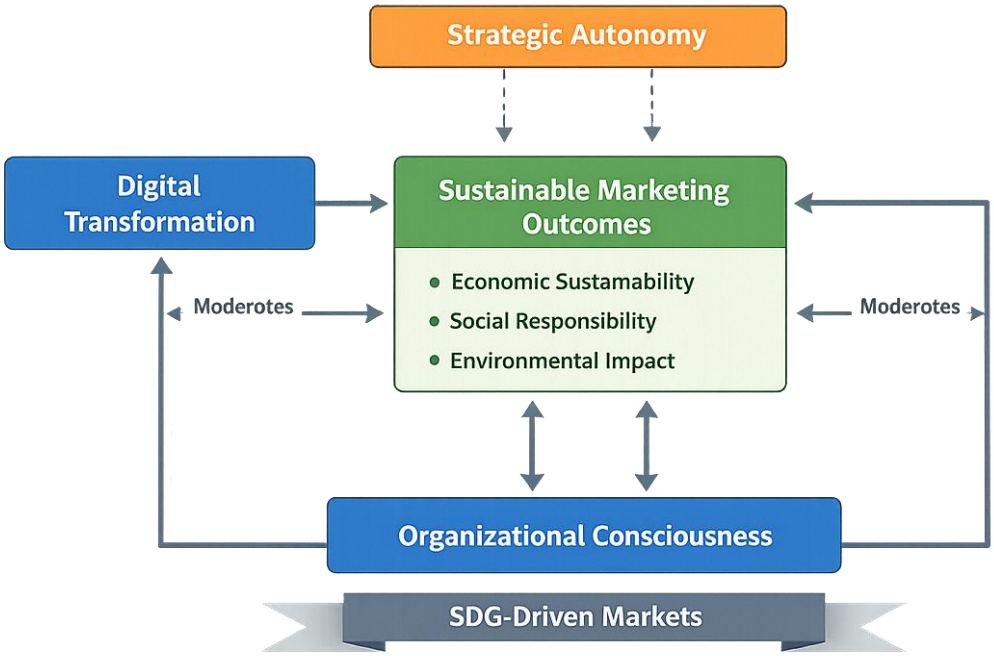


Figure 1. Intelligence-enabled sustainable marketing framework for SDG-driven markets[3].

[3] Source: Authors own work

2.6 Conceptual Integration

The proposed Intelligence–Governance–Consciousness mechanism aligns with competitiveness research emphasizing that Competitive Intelligence functions as a strategic capability rather than a purely informational activity. Prior studies show that intelligence capabilities support strategic coordination, anticipatory decision-making, and long-term competitiveness under conditions of uncertainty [16].

Research on internal marketing and strategic alignment further indicates that sustainable competitive positioning depends on the internal coordination of values, intelligence, and governance structures, rather than on isolated marketing actions (Papasolomou and Vrontis, 2006). These insights reinforce the argument that sustainable marketing effectiveness emerges through governance-level integration rather than normative intent alone.

Within the proposed framework, organizational consciousness arises as a higher-order strategic outcome produced by sustained intelligence processes operating within explicit governance boundaries. Consistent with emerging perspectives on sustainable competitiveness, this form of system-level awareness enables firms to anticipate sustainability-related risks, align with evolving stakeholder expectations, and achieve durable competitive advantage [16] [3].

3. Discussion

This paper advances the argument that sustainable marketing in SDG-driven markets must be reconceptualized as an intelligence-enabled governance capability rather than a predominantly normative or communicative function. By integrating sustainable marketing, digital transformation, and Competitive Intelligence (CI), the discussion interprets how firms can navigate sustainability under conditions of uncertainty, regulatory dynamism, and technological acceleration. The conceptual framework and propositions collectively illuminate a shift from reactive sustainability practices toward anticipatory, system-aware marketing strategy.

3.1 From Normative Sustainability to Anticipatory Marketing Strategy

Sustainable marketing research has traditionally emphasized ethical intent, corporate responsibility, and stakeholder alignment [2] [3]. While these perspectives underscore the importance of sustainability commitments, they often treat sustainability as a static objective rather than a dynamic strategic challenge. In SDG-driven markets, sustainability expectations evolve continuously as regulations, stakeholder norms, and competitive practices change [1].

Proposition P1 extends sustainable marketing theory by positioning Competitive Intelligence as the mechanism through which firms can anticipate such change. CI enables

organizations to move beyond post hoc compliance by systematically monitoring weak signals related to emerging sustainability standards, stakeholder discourse, and competitor initiatives [7]. As a result, sustainability becomes an anticipatory strategic orientation rather than a reactive obligation. This reframing addresses calls within the sustainability literature to move from moral aspiration toward strategic integration under uncertainty [4].

3.2 Digital Transformation Requires Interpretive Mediation

The discussion further clarifies the role of digital transformation in sustainable marketing. Digital technologies have expanded firms' ability to collect, process, and deploy market data at scale, enhancing efficiency and responsiveness [5]. However, Proposition P2 highlights that digital transformation alone does not ensure sustainability-aligned marketing outcomes.

Data-driven marketing systems are often optimized for short-term performance indicators such as engagement, growth, and conversion, which may conflict with long-term social and environmental objectives [6]. Competitive Intelligence mediates this relationship by introducing interpretation, contextual judgment, and temporal depth into digital systems. CI transforms data into foresight by distinguishing transient market noise from structurally significant sustainability trends. In doing so, it mitigates the risk of technologically deterministic marketing strategies that prioritize efficiency over societal impact.

3.3 Competitive Intelligence and the Emergence of Organizational Consciousness

A central contribution of this paper is the conceptualization of organizational consciousness as an outcome of sustained intelligence capability. As articulated in Proposition P3, consciousness refers to second-order organizational awareness of the systemic economic, social, and environmental consequences of market actions. This notion builds on sensemaking theory, which emphasizes how organizations interpret complexity and ambiguity through collective cognitive processes [9].

Competitive Intelligence facilitates the development of such consciousness by integrating heterogeneous information sources – including market data, regulatory signals, stakeholder expectations, and societal trends – into coherent strategic interpretations. Over time, intelligence-enabled marketing functions develop reflexivity regarding their broader societal role. This shift extends marketing theory beyond knowledge accumulation toward system-level awareness, suggesting that competitive advantage in SDG-driven markets increasingly depends on how firms interpret and internalize externalities rather than on information possession alone.

3.4 Strategic Autonomy as a Boundary Condition

Proposition P4 introduces strategic autonomy in digital infrastructure as a critical boundary condition shaping the effectiveness of intelligence-driven sustainable marketing. As firms become increasingly dependent on digital platforms, algorithmic systems, and external data providers, their ability to govern intelligence processes may be constrained [11].

From a sustainability governance perspective, insufficient control over data and digital infrastructures can undermine transparency, accountability, and regulatory compliance. Strategic autonomy – often framed as digital sovereignty – enhances firms' capacity to align intelligence systems with sustainability objectives and adapt to evolving governance regimes [13]. This insight situates sustainable marketing within broader debates on data governance and platform dependence, highlighting that sustainability outcomes are conditioned not only by intent and capability but also by infrastructural control.

3.5 Intelligence-Driven Sustainability and Durable Competitive Advantage

Proposition P5 integrates the preceding arguments by linking intelligence-driven sustainable marketing to durable competitive advantage. Prior research suggests that sustainability initiatives can enhance reputational capital and stakeholder trust [3], yet these benefits remain fragile when sustainability claims are inconsistent or weakly substantiated.

Competitive Intelligence strengthens sustainability outcomes by enabling continuous monitoring, verification, and adaptation of marketing practices to evolving societal standards. From a resource-based and dynamic capabilities perspective, intelligence-enabled sustainability constitutes a valuable, rare, and difficult-to-imitate capability embedded within organizational routines [14] [15]. As such, sustainability shifts from a cost or compliance burden to a source of long-term resilience and legitimacy when guided by robust intelligence systems.

3.6 Integrative Implications

Taken together, the discussion highlights a broader transformation in the role of marketing within SDG-driven markets. Rather than functioning solely as a persuasive interface with consumers, marketing increasingly operates at the intersection of markets, technology, and governance. Competitive Intelligence serves as the connective tissue linking digital transformation to sustainability imperatives, enabling firms to move from knowledge accumulation toward organizational consciousness.

This integrative perspective contributes to sustainable marketing theory by specifying the mechanisms through which sustainability becomes strategically actionable. It also extends Competitive Intelligence research by situating CI within societal and governance contexts rather than limiting it to competitor analysis. Ultimately, the discussion positions

intelligence-enabled sustainable marketing as a foundational capability for firms seeking long-term competitiveness in regulated, data-intensive, and sustainability-oriented market environments.

4. Future Research Directions and Implications

The intelligence-enabled sustainable marketing framework developed in this paper is intended as a platform for future scholarly inquiry rather than a closed theoretical model. By integrating sustainable marketing, digital transformation, and Competitive Intelligence (CI), the framework raises several empirical, managerial, and institutional questions that warrant further investigation in SDG-driven markets.

4.1 Future Research Directions

Firstly, future research should empirically examine the mediating role of Competitive Intelligence in the relationship between digital transformation and sustainable marketing effectiveness. While prior studies have independently linked digital transformation to performance outcomes [5] and sustainability initiatives to reputational and legitimacy benefits [3], limited empirical work has examined how intelligence capabilities translate digital data into anticipatory sustainability-oriented marketing decisions. Longitudinal and mixed-method research designs could test Propositions P1 and P2 by analyzing how CI maturity influences firms' ability to anticipate regulatory change, stakeholder expectations, and sustainability-related market shifts over time.

Secondly, the construct of organizational consciousness introduced in this paper requires further conceptual refinement and operationalization. Consciousness has been defined here as second-order organizational awareness of the systemic economic, social, and environmental consequences of market actions, extending sensemaking perspectives beyond knowledge accumulation [9]. Future research could develop and validate measurement scales capturing reflexivity, system-level interpretation, and ethical foresight in marketing decision-making. Qualitative approaches, including case studies and ethnographic research, may be particularly valuable in examining how such consciousness emerges through intelligence processes and governance routines.

Thirdly, comparative institutional research is needed to examine the moderating role of strategic autonomy and digital sovereignty. Firms operate within heterogeneous regulatory, technological, and institutional environments that shape data governance, platform dependence, and intelligence practices [11]. Cross-country and cross-industry studies could investigate how variations in data protection regimes, ESG disclosure mandates, and digital infrastructure control influence the effectiveness of intelligence-driven sustainable marketing strategies, thereby empirically testing Proposition P4.

Finally, future research should assess the long-term competitive outcomes associated with intelligence-driven sustainable marketing. While sustainability initiatives have been linked to trust, legitimacy, and reputational capital [2] [3], empirical evidence on their durability remains fragmented. Longitudinal studies connecting CI-enabled sustainability practices to resilience, adaptive capacity, and sustained competitive advantage would strengthen the dynamic capabilities perspective advanced in this paper [15], addressing Proposition P5.

4.2 Managerial Implications

For managers, the framework underscores the need to reconceptualize marketing as a coordinating and governance-oriented capability rather than a purely communicative function. Sustainable marketing initiatives are most effective when supported by systematic intelligence processes that enable firms to anticipate societal expectations, verify sustainability claims, and adapt strategies proactively. Embedding CI within marketing decision-making can reduce the risks of greenwashing and reactive compliance while enhancing strategic alignment with SDG objectives.

The findings also highlight the strategic importance of digital autonomy. Managers should critically assess the extent to which their digital infrastructures, analytics platforms, and data governance practices support intelligence-driven sustainability initiatives. Investments in data transparency, ethical AI, and internal intelligence capabilities can strengthen both marketing credibility and strategic flexibility in increasingly regulated and data-intensive markets.

4.3 Policy and Governance Implications

At the policy level, the framework suggests that sustainable marketing increasingly operates within governance-intensive ecosystems shaped by SDG reporting standards, ESG regulation, and data protection regimes [1]. Policymakers and standard-setting bodies should recognize the role of intelligence systems in enabling credible sustainability practices and consider how regulatory frameworks can support transparency, accountability, and data sovereignty without constraining innovation.

Moreover, the integration of CI and sustainable marketing has implications for public–private collaboration. Intelligence-enabled marketing systems may facilitate more effective partnerships around SDG implementation by aligning corporate strategies with societal objectives through shared metrics, interoperable data infrastructures, and stakeholder participation mechanisms. Such alignment could enhance the collective capacity of markets to contribute meaningfully to sustainable development goals.

In sum, by identifying empirical priorities, governance challenges, and strategic implications, it clarifies how intelligence-enabled sustainable marketing can guide both scholarly inquiry and organizational action in SDG-driven market environments.

5. Conclusion

This conceptual paper set out to reconceptualize sustainable marketing in the context of SDG-driven markets by integrating insights from sustainable marketing, digital transformation, and Competitive Intelligence (CI). Responding to growing calls for more strategic and system-level approaches to sustainability, the paper advances the argument that marketing can no longer be understood solely as a communicative or normative function. Instead, sustainable marketing increasingly operates as an intelligence-enabled governance capability that mediates between market dynamics, digital infrastructures, and societal expectations.

By adopting a societal evolution lens distinguishing between information, knowledge, and organizational consciousness, the paper highlights a fundamental shift in how marketing creates and governs value. While digital transformation expands firms' informational capacity, it does not automatically yield sustainability-aligned outcomes [5] [6]. Competitive Intelligence provides the interpretive and anticipatory mechanisms through which digital data is translated into strategic foresight, enabling firms to sense emerging sustainability pressures and respond proactively rather than reactively [7] [15].

A central contribution of this study is the conceptualization of organizational consciousness as a higher-order outcome of sustained intelligence capability. Framed as second-order organizational awareness of the systemic economic, social, and environmental consequences of market actions, consciousness extends beyond knowledge accumulation toward reflexive, system-aware marketing governance [9]. This framing clarifies how firms can internalize sustainability imperatives and align marketing strategies with the broader objectives of the Sustainable Development Goals [1].

The paper further demonstrates that the effectiveness of intelligence-driven sustainable marketing is conditioned by strategic autonomy in digital infrastructure. As firms become increasingly dependent on platform-based systems and external data ecosystems, their capacity to govern intelligence processes and ensure accountability may be constrained [11]. Strategic autonomy enhances firms' ability to align intelligence systems with sustainability objectives, adapt to regulatory requirements, and maintain stakeholder trust, positioning digital governance as a critical component of sustainable marketing strategy.

Collectively, the propositions and conceptual framework developed in this paper contribute to marketing theory in three important ways. First, they specify Competitive Intelligence as

the missing operational link between sustainability commitments and strategic execution. Second, they extend digital transformation research by emphasizing interpretive mediation rather than technological determinism. Third, they reposition marketing as a coordinating function within sustainability governance systems rather than as a purely persuasive market interface.

In essence, the paper proposes that digital capability contributes to sustainable marketing outcomes only when mediated by Competitive Intelligence and constrained by strategic autonomy, emphasizing that digital transformation is a necessary but insufficient condition for sustainability.

While the paper is conceptual in nature, its implications extend to empirical research, managerial practice, and policy development. By articulating how sustainability imperatives, digital capabilities, and intelligence processes interact, the framework provides a foundation for future studies examining marketing strategy in increasingly regulated, data-intensive, and sustainability-oriented market environments. Ultimately, the paper suggests that firms capable of integrating intelligence into sustainable marketing are better positioned to achieve durable competitive advantage while contributing meaningfully to societal goals

References

[1] UNITED NATIONS - *Transforming our world: The 2030 agenda for sustainable development*. ST(02)/T77. Published by United Nations, New York. 2015

[2] MAIGNAN, I., FERRELL, O.C. - *Corporate social responsibility and marketing: an integrative framework*'. Journal of the Academy of Marketing Science. ISSN: 0092-0703, ISSN-L: 0092-0703. 32(1). [pp. 3–19]. 2004

[3] PORTER, M.E., KRAMER, M.R. - *Creating shared value*. Harvard Business Review. ISSN: 0017-8012. 89(1–2). [pp. 62–77]. 2011

[4] HAHN, T., PINKSE, J., PREUSS, L., FIGGE, F. - *Tensions in corporate sustainability: towards an integrative framework*. Journal of Business Ethics. ISSN: 0167-4544, EISSN: 1573-0697. 127(2). [pp. 297-316]. 2015

[5] VERHOEF, P.C., BROEKHUIZEN, T., BART, Y., BHATTACHARYA, A., DONG, J.Q., FABIAN, N., HAENLEIN, M. - *Digital transformation: a multidisciplinary reflection and research agenda*. Journal of Business Research. ISSN: 0148-2963, Online ISSN: 1873-7978. 122. [pp. 889–901]. 2021

[6] Zuboff, S. - *The age of surveillance capitalism: the fight for a human future at the new frontier of power*. ISBN: 978-1610395694. Published by PublicAffairs, New York. 2019

[7] CALOF, J.L., WRIGHT, S. - *Competitive Intelligence: A practitioner, academic and inter-disciplinary perspective*. European Journal of Marketing. ISSN: 0309-0566, e-ISSN: 1758-7123. 42(7-8), [pp. 717–730]. 2008

[8] VĂTĂMĂNESCU, E.M., ANDREI, A.G., ALEXANDRU, V.-A., PÎNZARU, F. - *Digital transformation and organisational learning mechanisms: A conceptual perspective from the knowledge-based view*. Journal of Information Systems and Operations Management. ISSN: 1843-4711. 16(1). [pp. 37–49]. 2022

[9] Weick, K.E. *Sensemaking in organizations*. ISBN: 978-0803971776. Published by Sage, Thousand Oaks, CA. 1995

[10] FREEMAN, R.E., HARRISON, J.S., WICKS, A.C., PARMAR, B.L., DE COLLE, S. *Stakeholder theory: The state of the art*. ISBN: 978-0521137935. Published by Cambridge University Press, Cambridge. 2010

[11] VAN DIJCK, J., POELL, T., DE WAAL, M. - *The platform society: public values in a connective world*. ISBN: 978-0190889777. Published by Oxford University Press, Oxford.

[12] NARVER, J.C., SLATER, S.F. - *The effect of a market orientation on business profitability*. Journal of Marketing. ISSN: 0022-2429, e-ISSN: 1547-7185. 54(4). [pp. 20–35]. 1990

[13] HENTZEN, P.-Y. - *European Union puts its digital sovereignty to the test*. Stormshield, Available at: https://www.stormshield.com (Accessed: 30 January 2025). 2025.

[14] BARNEY, J.B. - *Firm resources and sustained competitive advantage*. Journal of Management. ISSN: 0149-2063, e-ISSN: 1557-1211. 17(1). [pp. 99–120]. 1991

[15] TEECE, D.J. - *Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance*. Strategic Management Journal. ISSN:0143-2095, e-ISSN:1097-0266. 28(13). [pp. 1319–1350]. 2007

[16] CAVALLO, A., SANASI, S., GHEZZI, A., RANGONE, A. - *Competitive Intelligence and Strategy Formulation: Connecting the Dots.* Competitiveness Review. ISSN: 1059-5422, e-ISSN: 2051-3143. 31(2). [pp. 250–268]. 2020

[17] PAPASOLOMOU, I., VRONTIS, D. - *Building corporate branding through internal marketing: the case of the UK retail bank industry*. Journal of Product & Brand Management. 15(1). ISSN: 1061-0421, e-ISSN: 2054-1643. [pp. 37–47]. 2006

Bibliography

Barney, J.B. (1991), 'Firm resources and sustained competitive advantage', *Journal of Management*, 17(1), pp. 99–120.

Calof, J.L. and Wright, S. (2008), 'Competitive Intelligence: A practitioner, academic and inter-disciplinary perspective', *European Journal of Marketing*, 42(7-8), pp. 717–730.

Cavallo, A., Sanasi, S., Ghezzi, A. and Rangone, A. (2020), 'Competitive Intelligence and Strategy Formulation: Connecting the Dots', *Competitiveness Review*, Vol. 31 No. 2, pp. 250–268.

Freeman, R.E., Harrison, J.S., Wicks, A.C., Parmar, B.L. and de Colle, S. (2010), *Stakeholder theory: the state of the art*, Cambridge University Press, Cambridge.

Hahn, T., Pinkse, J., Preuss, L. and Figge, F. (2015), 'Tensions in corporate sustainability: towards an integrative framework', *Journal of Business Ethics, 127(2),* pp. 297-316.

Hentzen, P.-Y. (2025), 'European Union puts its digital sovereignty to the test', *Stormshield*, Available at: https://www.stormshield.com (Accessed: 30 January 2025).

Maignan, I. and Ferrell, O.C. (2004), 'Corporate social responsibility and marketing: an integrative framework', *Journal of the Academy of Marketing Science*, 32(1), pp. 3–19.

Narver, J.C. and Slater, S.F. (1990), 'The effect of a market orientation on business profitability', *Journal of Marketing*, 54(4), pp. 20–35.

Papasolomou, I. and Vrontis, D. (2006), 'Building corporate branding through internal marketing: the case of the UK retail bank industry', *Journal of Product & Brand Management*, Vol. 15 No. 1, pp. 37–47.

Porter, M.E. and Kramer, M.R. (2011), Creating shared value, *Harvard Business Review*, 89(1–2), pp. 62–77.

Teece, D.J. (2007), 'Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance', *Strategic Management Journal*, 28(13), pp. 1319–1350.

United Nations (2015), *Transforming our world: the 2030 agenda for sustainable development*, United Nations, New York.

Van Dijck, J., Poell, T. and de Waal, M. (2018), *The platform society: public values in a connective world*, Oxford University Press, Oxford.

Vătămănescu, E.M., Andrei, A.G., Alexandru, V.-A. and Pînzaru, F. (2022) 'Digital transformation and organisational learning mechanisms: A conceptual perspective from the knowledge-based view', *Journal of Information Systems and Operations Management*, 16(1), pp. 37–49.

Verhoef, P.C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J.Q., Fabian, N. and Haenlein, M. (2021), 'Digital transformation: a multidisciplinary reflection and research agenda', *Journal of Business Research*, 122, pp. 889–901.

Weick, K.E. (1995), *Sensemaking in organizations*, Sage, Thousand Oaks, CA.

Zuboff, S. (2019), *The age of surveillance capitalism: The fight for a human future at the new frontier of power*, PublicAffairs, New York.

NAVIGATING ANNUAL FINANCIAL REPORTING IN EUROPEAN SINGLE ELECTRONIC FORMAT (ESEF): A GUIDE FOR EU-LISTED COMPANIES

Cosmin Ionuț LUNGU[1]

Abstract

Electronic reporting in the European Single Electronic Format[2] (ESEF) refers to the standardized format used by listed issuers within the European Union to prepare and submit their annual financial reports. This format was introduced by the European Securities and Markets Authority[3] (ESMA) in line with the European Union Transparency Directive (TD) and is designed to facilitate the digitalization of financial reporting for publicly listed companies.

Keywords: ESEF, RTS on ESEF, ESEF Taxonomy, ESMA, Annual Financial Reports, XBRL, XHTML, Financial Statements, Management report, Sustenabilty reporting.

JEL Classification: M40, M41, M42, M48, M49

1. Introduction

In 2013 the Transparency Directive (Directive 2004/109/EC), which sets rules on harmonisation of transparency requirements of issuers, was amended to include, amongst others, a requirement for issuers to prepare their annual financial reports (AFRs) in a single electronic reporting format (ESEF).

ESMA was assigned the responsibility to develop regulatory technical standards (RTS) to specify this electronic reporting format. The detailed provisions of the ESEF and the underlying policy choices are contained in the original Final Report on the RTS on ESEF. ESMA yearly amends the RTS on ESEF (latest Final Report on the RTS on ESEF) to

[1] PhD Lecturer, Department of Finance, Credit, Accounting at Romanian American University, Romania, ionut.lungu@rau.ro

2 Electronic Reporting - Digitalisation enhances the accessibility, analysis, and comparability of annual financial reports. The European Single Electronic Format (ESEF) is the mandated electronic reporting format for issuers with securities traded on EU regulated markets. ESMA develops the regulatory technical standards (RTS) that define this format, along with providing guidance and implementing tools.

3 The European Securities and Markets Authority (ESMA) is a key regulatory body in the European Union, and its mission is focused on enhancing the stability, integrity, and efficiency of financial markets in Europe. ESMA is part of the broader European System of Financial Supervision (ESFS), which includes the European Banking Authority (EBA) and the European Insurance and Occupational Pensions Authority (EIOPA). Together, these institutions aim to ensure the stability and safety of the financial system in the EU.

incorporate the necessary updates on the ESEF taxonomy and developments in the market. The European Single Electronic Format (ESEF) is an XML-based format that enables listed companies to prepare their financial reports in a standardized, machine-readable format. The purpose of ESEF is to improve transparency, accessibility, and comparability of financial information across the European Union. It aims to make it easier for regulators, investors, and analysts to access and analyze corporate financial information across different jurisdictions.

The Format of the ESEF is based on Inline XBRL (iXBRL), which combines human-readable HTML with machine-readable XBRL tags, allowing both easy viewing and data extraction for further analysis.

An annual financial report for a listed issuer typically consists of several key components that provide a comprehensive overview of the company's financial performance and position for the year. These reports are essential for investors, regulators, analysts, and other stakeholders to assess the company's financial health, its compliance with accounting standards, and its future prospects. For a listed issuer in the European Union, the annual financial report is required to be prepared according to International Financial Reporting Standards (IFRS), and it must comply with the ESEF (European Single Electronic Format) regulation for submission and accessibility.

2. Content of annual financial report for a listed issuer

2.1 Management Report

The management report is a narrative section that provides context to the company's financial results and operations. It includes insights from the management team on the company's performance, strategy, and outlook.

Key components of the management report:

- **Business Review:** Overview of the company's business activities during the year. Key highlights of the company's operations, including significant events (acquisitions, divestitures, new product launches, etc.). Market overview and performance relative to industry peers.
- **Financial Performance:** An explanation of the financial results presented in the financial statements (e.g., revenue, profit, etc.). Key financial ratios or metrics used by management to assess company performance.
- **Risk Management:** A description of the company's risk profile, including both financial and non-financial risks (market risk, credit risk, liquidity risk, operational risk, etc.). Details on how the company manages and mitigates these risks.
- **Corporate Governance:** Overview of the company's governance framework, including the structure of the Board of Directors, committees, and executive management. Compliance with governance codes and regulations.

- **Sustainability and ESG (Environmental, Social, Governance) Reporting:** For companies focusing on sustainability, a section dedicated to ESG performance and initiatives might be included.
- **Future Outlook:** Management's perspective on the company's future performance, including strategic goals, expected market conditions, and potential challenges.

2.2 Financial Statements

The financial statements provide a detailed account of the company's financial performance and position over the reporting period. These must be prepared according to IFRS standards.

Key components of the financial statements are:

- **Balance Sheet (Statement of Financial Position):** Assets: What the company owns (e.g., cash, receivables, inventory, property, plant, and equipment); Liabilities: What the company owes (e.g., loans, payables, long-term debt); Equity: The shareholders' stake in the company, including share capital, retained earnings, and other reserves.
- **Income Statement (Statement of Performance):** Revenue: The total income from sales of goods or services. Cost of Goods Sold (COGS): The direct costs associated with producing goods or services. Operating Expenses: Administrative, marketing, and other operational costs. Net Income or Loss: The company's profit or loss after accounting for all revenues and expenses.
- **Statement of Cash Flows:** Provides information about the company's cash inflows and outflows during the reporting period, classified into: Operating Activities: Cash generated or used in the day-to-day business operations. Investing Activities: Cash used for purchasing or selling long-term assets like property or investments. Financing Activities: Cash flows from issuing or repaying debt or equity.
- **Statement of Changes in Equity:** Shows how the company's equity has changed over the reporting period due to factors like profits, dividends, share issuance, or repurchase of shares.
- **Notes to the Financial Statements:** Detailed explanations of the numbers in the financial statements, such as accounting policies, assumptions, and breakdowns of specific line items (e.g., details of debt or pension liabilities). Information on related-party transactions, contingencies, and legal matters. Any adjustments made during the period that affect the financial statements.

2.3 Auditor's Report

The auditor's report provides an independent evaluation of the company's financial statements. It is issued by a third-party external auditor and provides an opinion on whether the financial statements: Present a true and fair view of the company's financial position

and performance. Comply with applicable accounting standards (e.g., IFRS). Are free from material misstatements or fraud.

Types of opinions an auditor can issue:

- Unqualified Opinion (Clean): The financial statements are free from material misstatements.
- Qualified Opinion: There are issues with the financial statements, but they are not material enough to affect the overall opinion.
- Adverse Opinion: The financial statements are materially misstated and do not present a true and fair view.
- Disclaimer of Opinion: The auditor could not obtain sufficient evidence to form an opinion.

2.4 Corporate Governance Report

This section outlines the company's approach to corporate governance, including its adherence to best practices and applicable governance codes (e.g., UK Corporate Governance Code, German Corporate Governance Code). Key items in the corporate governance report may include:

Structure and composition of the Board of Directors and any committees (audit, remuneration, nomination, etc.). Independence of directors. Diversity and board member qualifications. Executive compensation and incentive structures. Shareholder rights and how they are safeguarded. The company's compliance with governance codes and explanations of any deviations.

2.5 Directors' Report / Board of Directors' Statement

The Directors' Report (or Board of Directors' Statement) typically provides additional information beyond the financial statements, offering insight into the management's strategy, performance, and significant changes or events during the year. It includes: A summary of business operations. Information on the market environment and key risks the company faces. Key performance indicators (KPIs).

Details about any significant changes in the company, including acquisitions, mergers, or restructurings.

2.6 Shareholder Information

This section provides important information to shareholders, including:

Dividend policy and any dividends declared for the year. Share capital structure, including the total number of shares and any changes. Ownership structure, if relevant, including major shareholders or changes in control. Annual General Meeting (AGM) details, including date, time, and agenda. Corporate social responsibility (CSR) activities, if applicable.

2.7 Other Regulatory Disclosures

Depending on the company's jurisdiction and industry, other regulatory disclosures may be required. These could include: Related party transactions. Contingent liabilities. Environmental, Social, and Governance (ESG) disclosures, especially for companies that are focused on sustainability. Compliance with local or international regulations. Tax-related disclosures, including tax positions and any ongoing audits or disputes.

2.8 Supplementary Financial Information

Interim Financial Reports: Some listed companies may provide an interim financial report for the first half of the financial year, which includes condensed financial statements and a management discussion. Key Metrics and Ratios: Common metrics such as earnings per share (EPS), return on equity (ROE), and debt-to-equity ratio might also be disclosed to help investors assess the company's financial health.

3. ESEF Filing Requirements

For a listed issuer in the EU (Tabel 1 presents the number of issuers in EU Countries (EU27) – 6.930 issuers admited to tranding on a regulated), the annual financial report must be filed in ESEF format (using iXBRL for tagging), which includes: Tagging the primary financial statements (balance sheet, income statement, etc.) and notes to the financial statements with XBRL tags. Ensuring the management report is filed in compliance with the ESEF taxonomy[4]. Submitting the report electronically through the relevant National Competent Authority[5] (NCA) and ensuring it is publicly accessible.

Based on IFRS: The ESEF format is designed to work with financial statements prepared according to International Financial Reporting Standards (IFRS), which is the mandatory accounting framework for companies listed on EU regulated markets.

XBRL Tagging: A key aspect of ESEF reporting is the XBRL tagging of key financial data points. These tags correspond to specific concepts in the ESEF taxonomy, which is based on the IFRS taxonomy but includes additional elements specific to the ESEF requirements.

Annual Financial Reports: ESEF applies to annual financial reports (consolidated financial statements) and includes both the financial statements and the management report. Companies must tag their financial data, such as the balance sheet, income statement, and cash flow statement, as well as their notes to the financial statements.

Filing Requirement for Listed Companies: All EU-listed companies (approximate 7000 those listed on regulated markets. Number of issuers per country is presedted below based on the esma reports as at june 2025) are required to prepare their annual financial reports in ESEF format, starting from the fiscal year 2020. This requirement ensures that all public

[4] The ESEF (European Single Electronic Format) taxonomy is a standardized, digital dictionary based on the IFRS Taxonomy, mandated by ESMA for EU-listed companies to tag annual financial reports.

5 In Romania, for example, the National Competent Authority (NCA) is Autoritatea de Supraveghre Financiară (https://www.asfromania.ro/).

companies within the EU adhere to the same standard when submitting their financial information.

Country	Austria	Belgium	Bulgaria	Cyprus	Czechia	Germany	Denmark	Estonia	Greece	Spain	Finland	France	Croatia	Hungary	Ireland	Sweden	Italy	Lithuania	Luxembourg	Latvia	Malta	Netherlands	Poland	Portugal	Romania	Slovenia	Slovakia	TOTAL
Issuers no	104	156	299	61	110	553	195	35	143	188	174	595	82	59	1241	2	293	34	877	19	92	303	479	57	101	588	90	**6930**

Tabel 1 – Number of issuers in EU Countries (EU27)

Public Accessibility: Once submitted, these reports are publicly available on the public register maintained by the relevant National Competent Authority (NCA). This enhances transparency, as anyone can access and analyze the data in machine-readable format.

The ESEF report generally consists of:

- Primary financial statements.
- Notes to the financial statements: These notes must also be tagged with appropriate XBRL tags, providing further context for the financial data.
- Management Report: This section must also be prepared and submitted in the iXBRL format, though some flexibility exists depending on the jurisdiction.
- Tagging of Key Financial Metrics: Key data points in the financial statements, such as total assets, net income, or revenue, must be tagged with specific XBRL tags to provide clarity on what each figure represents.

The ESEF taxonomy is a collection of standardized tags that map to the IFRS taxonomy and prvide definitions for financial concepts used in the reports.

XBRL Tags: The taxonomy includes predefined tags for common financial data points such as revenue, net income, and total assets. Companies use these tags when preparing their financial reports.

ESEF-Specific Extensions: While the ESEF taxonomy is largely based on IFRS, it also includes specific extensions that are required for the ESEF format, such as tags for the management report and other disclosures.

4. ESEF Compliance Timeline

4.1 Who Needs to Comply with ESEF?

- Listed Companies: All companies listed on EU-regulated markets are required to submit their annual consolidated financial reports in ESEF format.

- IFRS Preparers: The format is specifically intended for companies that prepare their financial statements in accordance with International Financial Reporting Standards (IFRS), which is required for most companies listed in the EU.

The ESEF reporting requirement applies to financial statements for fiscal years starting on or after January 1, 2020.

The first submissions in iXBRL format were due in 2021, based on the 2020 financial year, but companies with earlier financial years (e.g., those following a calendar year) had deadlines in 2021 or early 2022.

Companies must submit their ESEF-compliant financial reports no later than four months after the end of the financial year (typically by April 30 for companies with a December 31 year-end).

4.2 How to Submit ESEF Reports?

National Competent Authorities (NCAs): Companies must submit their ESEF reports to the national regulator (e.g., ASF in Romania, AMF in France, or BaFin in Germany).

Public Access: Once submitted and accepted by the NCA, the reports are publicly available for investors, analysts, and other stakeholders to access through the regulator's public register.

5. Tools for ESEF Reporting

To prepare, tag, and submit reports in ESEF format, companies generally rely on specialized software tools, including: XBRL Tagging Tools (e.g., CoreFiling, Workiva, IRIS Carbon, XBRLCloud)

Validation Tools to ensure the reports meet ESEF technical specifications (e.g., ESMA's ESEF Filing Validation Tool).

These tools automate the process of tagging and ensure compliance with ESEF requirements. They also help ensure that the report is correctly structured and free of errors before submission.

Once submitted, the report is available on the public register maintained by the local competent authority. This is an open-access register, and stakeholders can download the reports in iXBRL format to analyze the data.

The RTS on ESEF specifies that all issuers subject to the requirements contained in the Transparency Directive to make public Annual Financial Reports shall prepare annual financial reports in the Extensible Hypertext Markup Language (XHTML) format. Where the issuer prepares IFRS consolidated financial statements, it shall mark up these IFRS consolidated financial statements using the XBRL markup language. The mark ups shall be

embedded in the XHTML document version of the annual financial report using the Inline XBRL format.

The European Securities and Markets Authority (ESMA), the EU's financial markets regulator and supervisor, has today published the 2024 European Single Electronic Format (ESEF) XBRL taxonomy files and an update to the ESEF Conformance Suite to facilitate the implementation of the ESEF Regulation.

ESMA aims to support the implementation of the ESEF by providing XBRL taxonomy files and Conformance Suite test files that align with the requirements of the 2024 draft update to the ESEF Regulation and the 2024 update to the ESEF Reporting Manual.

Today's publication intends to assist software vendors and issuers in preparing the 2024 IFRS consolidated financial statements using the most updated version of the ESEF format. It will also facilitate EU issuers listed on US capital markets (known as 'Foreign Private Issuers') in meeting their reporting obligations with the US Securities and Exchange Commission (SEC). Nevertheless, the 2024 ESEF taxonomy files and the updated Conformance Suite will only discharge issuers from their EU ESEF obligations for their annual financial reports concerning financial years beginning on or after 1 January 2024 after the entry into force of the 2024 update to the ESEF Regulation.

Issuers may alternatively use the 2022 ESEF taxonomy files and conformance suite published by ESMA in December 2022, for annual financial reports concerning financial years beginning on or after 1 January 2024.

The 2024 draft update to the ESEF Regulation was submitted by ESMA in May 2024, adopted by the European Commission on 27 September 2024 and cleared the scrutiny of the European Parliament and Council on 27 December 2022 without objection.

In 2023, ESMA decided to postpone to 2024 the amendment of the ESEF RTS to reflect the limited changes of the 2023 update of the IFRS taxonomy and focus on monitoring the implementation of the ESEF requirements and how to improve the electronic reporting process. The 2024 ESEF taxonomy incorporates the latest updates to the International Financial Reporting Standards (IFRS) taxonomy from 2023 and 2024, developed annually by the IFRS Foundation. The IFRS Foundation also publishes a versioning document detailing changes from previous taxonomies. The ESEF taxonomy package includes labels in all EU languages.

Under the ESEF Regulation, all issuers with securities listed on an EU regulated market must prepare their annual financial reports in xHTML and mark-up the IFRS consolidated financial statements using XBRL tags and iXBRL technology.

The 2024 update to the ESEF regulation will take effect on the twentieth day following its publication in the European Official Journal, which is expected by mid-January 2025.

Digitalisation enhances the accessibility, analysis, and comparability of annual financial reports. The European Single Electronic Format (ESEF) is the mandated electronic reporting format for issuers with securities traded on EU regulated markets. ESMA develops the regulatory technical standards (RTS) that define this format, along with providing guidance and implementing tools. ESEF background

6. Enforcement Process by the National Competent Authorities (NCAs)

Once the reports are filed, the National Competent Authorities (NCAs) are responsible for ensuring that the submitted reports comply with the ESEF regulations. This is part of the broader enforcement process under ESMA's guidelines.

6.1. NCA Review

The NCAs review the ESEF filings to check for:

- **Compliance** with technical standards (correct XBRL tagging, proper formatting, etc.);
- **Accuracy** of financial data (whether the figures in the report are properly disclosed and consistent with other filings);
- **Timeliness** of filing (whether the company met the submission deadline).

6.2. Random Checks and Spot Inspections

NCAs may conduct random checks and spot inspections to verify the accuracy and completeness of the filings. They will also ensure that the company has used the appropriate XBRL tags from the ESEF taxonomy.

6.3. Possible Sanctions for Non-compliance

If a company does not comply with the ESEF requirements, the NCA may take various actions:

- **Requests for correction**: If errors are found, the company may be asked to correct and resubmit the report.
- **Fines**: Non-compliance with the filing format, such as failure to submit the iXBRL report or significant errors in tagging, can lead to penalties.
- **Public warnings**: In more serious cases, NCAs may issue public warnings about non-compliant filings.
- **Market scrutiny**: Regulators may also flag the company for further market scrutiny, which can affect investor confidence.

6.4. Follow-up Enforcement

NCAs can monitor whether the company addresses the issues raised during the review process. If the company fails to comply with correction requests, further penalties or sanctions may be applied.

7. Conclusions

Preaparing financial statements using IFRS/ESEF taxonomy when tagging financial statements' items can be an advantage in theory, but in business practice these advantages are challenges for many companies. Implementation will be successful only if preparers and users, benefit from such form of reporting. There is a crucial role of regulators, standard-setters, professional accounting institutions, academics, and researchers to inform and educate preparers by developing best practice examples, case-studies, simple user guides, and thus wider application, especially in the most represented group of the economy, which are small and medium-sized enterprises. As the time of mandatory application of the ESEF taxonomy in the EU is just ahead of us, it remains to be seen to what extent iXBRL adoption will affect the financial performance of the EU enterprises and in particular whether the perceived long-term benefits will outweigh possible short-term difficulties.

Summary of ESEF

- Determine applicability under EU rules.
- Prepare annual reports in XHTML format.
- Tag IFRS consolidated statements with iXBRL.
- Use current ESEF/IFRS taxonomy.
- Audit and review tagging quality.
- Submit to OAM by the statutory deadline

Benefits of ESEF

- **Improved Transparency:** By making financial reports available in a standardized, machine-readable format, ESEF improves the transparency of financial data across the EU.
- **Better Comparability**: Investors, analysts, and regulators can more easily compare financial data across companies, even if those companies are from different EU countries.
- **Greater Efficiency**: The use of a standardized format reduces the need for manual data entry and minimizes errors in the reporting process. It also facilitates faster data extraction and analysis.
- **Investor Confidence**: ESEF makes it easier for investors to access accurate and timely financial information, which can boost investor confidence in the financial markets.

References

[1] Marina MÄURER, Hendrik PEPER, Henning ZÜLCH - *The adoption of digital financial reporting formats in Germany: perceptions and experiences on the potential impacts of the ESEF regulation on the preparation, disclosure, and usage of annual reports*

- HHL Leipzig Graduate School of Management – HHL Working Paper No. 198. ISSN 1864-4562. Page 04-10. July 2022

[2] Marina ĐUROVIĆ, Ana REP, Nikolina DEČMAN – *Towards full digitalization of the financial reporting – overvew of the financial reporting languages* - Proceedings of FEB Zagreb 12th International Odyssey Conference on Economics and Business, Vol.3, No.1, Page 55-70, ISSN 2671-132X, June 2021, Zagreb

[3] Vladan MARTIC, Nermin Škretović, Nedžad LAJKA – *The role in importance of reporting in the uniform Europena Electronic Format (ESEF)* - page 68-70. ISBN 978-961-7110-10-4 Proceedings of the 6th EASTERN EUROPEAN CONFERENCE OF MANAGEMENT AND ECONOMICS (EECME 2024). June 2024.

[4] Hutteunen EEVI - *Introducing XBRL to case company's annual financial reporting process* - Lappeenranta-Lahti University of Technology LUT Pages 03-15, SSRN 5333749. May 2021

[5] *On the Path to an European Single Electronic Format – ESMA Consultation for the IFRS Taxonomy of Structured Electronic Reporting,* 10-11-2016, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2866747

[6] https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3336109 - he Annual Reports Becoming Digital - An Initial Field Analysis of the NYSE Listed IFRS-Filers. 07-03-2019

Bibliography

Beerbaum, D., Piechocki, M., & Puaschunder, J. - *Measuring Accounting Report- ing Complexity with customized extensions XBRL: A Behavioral Economics ap-proach*. Journal of Applied Research in the Digital Economy, 10(1), Page 03–41. April 2019

Drake, M. S., Hales, J., & Rees, L. (2019). Disclosure Overload? A Professional User Perspective on the Usefulness of General-Purpose Financial Statements. Contemporary Accounting Research, 36(4), 1935–1965. https://doi.org/10.1111/1911-3846.12488

EC. (2020). One-year optional ESEF postponement. European Commission. https://ec.europa.eu/info/publications/201211-esef-postponement_en

EC (2021). Proposal for a Directive of the European Parliament and of the Council amending Directive 2013/34/EU, Directive 2004/109/EC, Directive 2006/43/EC and Regulation (EU) No 537/2014, as regards corporate sustainability reporting: EC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021PC0189&from=EN

XBRL US. (2019). XBRL US Comment RE: SEC RFC on Earnings Releases & Quarterly Reports. XBRL US Comment RE: SEC RFC on Earnings Releases & Quarterly Reports

XBRL.org. (2019). iXBRL. https://www.xbrl.org/the-standard/what/ixbrl/

Zamzam, A., & A. Qaffas, A. (2018). Xbrl technologies for financial reporting in information systems. INTERNATIONAL JOURNAL of MANAGEMENT &INFORMATION TECHNOLOGY, 13, 3281–3287.

https://doi.org/10.24297/ijmit.v13i0.7609

Zhang, Y., Chen, Y., Luo, W., Zhang, J., & Wang, D. (2019). Game analysis of XBRL taxonomy extension. Cluster Computing, 22(S5), 12529–12538. https://doi.org/10.1007/s10586-017-1680-z

Final Report on draft RTS amending the taxonomy for the European Single Electronic Reporting (ESEF) - 2024

https://www.esma.europa.eu/document/final-report-draft-rts-amending-taxonomy-european-single-electronic-reporting-esef-2024

Updated 2025 IFRS taxonomy introduced into the European Single Electronic Format

https://www.esma.europa.eu/press-news/esma-news/updated-2025-ifrs-taxonomy-introduced-european-single-electronic-format

THE EVOLUTION OF SOFTWARE PROJECT MANAGEMENT REGARDING QUALITY AND SUCCESS

Luca Teodor MÂNDRU[1]

Andrei Radu COJOCARU[2]

Alexandra BURNICHI[3]

Costin Andrei VLAD[4]

Costin-Anton BOIANGIU[5]

Nicolae TARBĂ[6]

Abstract

This paper explores the evolution of software project management practices, focusing on the interplay between quality and project success. It highlights the shift from traditional methodologies like Waterfall to modern approaches such as Agile and hybrid frameworks, driven by the need to adapt to dynamic environments and evolving requirements. The study emphasizes the critical role of balancing quality, measured by defect rates, user satisfaction, system performance, and broader success metrics like cost, time, scope, and stakeholder satisfaction. Through historical analysis and case studies, the research identifies the limitations of linear methodologies and the advantages of iterative approaches. Agile emerges as a preferred model, demonstrating higher success rates due to its adaptability and continuous feedback cycles. Hybrid methodologies, combining the strengths of Agile and Waterfall, are increasingly adopted, particularly in large organizations seeking flexibility without sacrificing structure. Key findings suggest that success in software projects depends on selecting the right methodology, fostering collaboration, and leveraging advanced technologies. Insights from industry data underscore the correlation between effective quality practices and project success. The paper concludes by advocating for tailored,

[1] Stud., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, luca_teodor.mandru@acs.stud.pub.ro
[2] Stud., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, andrei.cojocaru0606@ acs.stud.ro
[3] Stud., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, alexandra.burnichi@ acs.stud.ro
[4] Stud., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, costin_andrei.vlad@ acs.stud.ro
[5] Prof., PhD, Eng., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, costin.boiangiu@cs.pub.ro
[6] PhD Stud., Eng., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, nicolae.tarba@upb.ro

hybrid approaches that balance predictability with responsiveness, enabling organizations to meet technical and business objectives in increasingly complex environments.

Keywords: Software Project Management, Agile Methodologies, Hybrid Frameworks, Waterfall Model, Quality Assurance in Software, DevOps and Continuous Integration, Artificial Intelligence in Project Management, Stakeholder Engagement

JEL Codes: L86, M15, O31, O32, M54, M53

1. Introduction

In the era of technology, effective management of software projects has become essential for achieving successful outcomes. An increasing number of companies are expressing interest in this field as they strive to deliver software solutions that meet both user expectations and business objectives.

1.1 Importance of quality and success in software project management

Maintaining a balance between quality and success is crucial in determining whether the software project achieves its intended goals. Quality refers to the degree to which a software product meets the requirements, satisfies user needs, and is free from defects. Success, on the other hand, is broader, encompassing not only the final product's quality but also factors such as time, cost, and stakeholder satisfaction. A project might be considered a failure if it exceeds its budget, misses deadlines, or fails to meet business objectives, even if the software itself is of high quality.

2. Fundamentals of Software Project Management

2.1 Definition and Basic Elements of Project Management

Project management is the discipline of planning [1], organizing, securing, managing, leading, and controlling resources to achieve specific goals within a defined timeline and budget. In the context of software development, project management involves balancing the complexities of time, scope, cost, and quality. Key elements of project management include the project lifecycle (initiation, planning, execution, monitoring, and closure), resource management, risk management, stakeholder management, and the use of various methodologies like Agile, Waterfall, or hybrid approaches.

The Agile methodology, for instance, emphasizes iterative progress through short cycles known as sprints, allowing teams to respond quickly to changes and maintain flexibility in meeting client needs. This contrasts with Waterfall, a more traditional linear approach, where each phase must be completed before the next begins. According to Boldare [1], Agile methodologies show high success rates in software project management due to their flexibility and iterative feedback loops. Ciupe et al. [2] showed that agile methodologies can also be applied to other domains such as higher education, thus showcasing their flexibility.

2.2 Evolution of Software Project Management Practices

Software project management has evolved significantly over the past decades. Traditional project management models, such as Waterfall, were initially dominant. These models, however, often struggled with rapidly changing requirements, poor communication, and a lack of flexibility. In response, Agile methodologies emerged in the early 2000s, advocating for smaller, iterative development cycles that are more adaptable to change.

The shift toward Agile is marked by the Agile Manifesto, which emphasizes collaboration, adaptability, and customer-centric development. In comparison, the Agile vs. Waterfall [3] debate reveals that Agile's flexible and iterative nature tends to lead to higher project success rates. Quixy, a software company that automates business processes, found that Agile projects have a 64% success rate [4], compared to a mere 49% for Waterfall projects. Agile's success lies in its ability to respond to feedback early and continuously, reducing the risk of project failure.

The use of Agile, alongside various project management tools and software, has increased over the years, making it easier for teams to coordinate, track progress, and adjust strategies as needed. Visual planning tools, for instance, have grown in popularity, offering dashboards that provide real-time updates on project progress, helping teams stay aligned and on track.

2.3 Defining and Measuring Project Success and Quality

Defining and measuring success in software project management requires understanding both the technical and business aspects of a project. Success can be measured in terms of whether the project is completed on time, within budget, and whether it meets the specified quality standards. However, success also extends to how well the software fulfills the client's needs and whether the team can maintain a sustainable and effective process.

Key performance indicators (KPIs) [5] commonly used in measuring project success include customer satisfaction, meeting deadlines, staying within budget, and achieving the

desired quality of the product. Quality in software development is typically measured using defect rates, user feedback, and system performance.

In terms of Agile, success is often measured by the frequency and quality of user feedback, as continuous feedback helps improve the software in each iteration. The shift to Agile practices has allowed for more dynamic and responsive project management, with 71% of Agile projects reported to have improved their quality over time, as highlighted by statistics from Zippia [6]. Furthermore, Agile encourages continuous improvement, helping teams refine their processes and deliver higher-quality outputs with each cycle.

Moreover, project quality can also be gauged through statistical insights, such as those provided by Visual Planning [7], where the application of proper planning and tracking systems significantly impacts the quality and timeliness of software deliveries.

To sum up, the evolution of software project management practices highlights the importance of choosing the right methodology, with Agile emerging as a preferred choice due to its adaptability, higher success rates, and focus on continuous quality improvement. Monitoring key metrics and using effective tools play a crucial role in ensuring that projects are completed successfully while meeting both the technical and business objectives.

3. Historical Perspectives on Software Project Management

3.1 Early Approaches and Methodologies: Limitations and Advantages

In the early stages of software project management, the focus was predominantly on linear, sequential methodologies. One of the earliest and most influential frameworks was the Waterfall methodology. This approach emphasized a structured, step-by-step process, where each phase—requirements gathering, design, development, testing, and deployment—was completed before moving to the next phase. The Waterfall model was based on the idea that the entire project could be planned upfront, making it easier to manage and track progress.

However, Waterfall had its limitations, particularly in dealing with changing requirements. Software projects often evolve and face unexpected challenges, but Waterfall's rigid structure made it difficult to incorporate changes once a phase was completed.

As noted in the PMI Talent Gap Report 2021 by the Project Management Institute (PMI), one of the key challenges identified in traditional project management methodologies is the difficulty in adjusting to shifting requirements during the project lifecycle, which can lead to delays and inefficiencies PMI Talent Gap Report [8]. Despite these limitations, Waterfall did offer some advantages, such as clear documentation and milestones, which made tracking progress straightforward. This approach worked best in situations where the

project requirements were well understood from the outset, and the project scope was unlikely to change significantly.

The evolution of software project management saw the rise of more adaptive approaches, especially with the advent of Agile methodologies. Agile broke away from the linear structure of Waterfall and embraced flexibility, emphasizing iterative development with short, incremental cycles (sprints). Agile was designed to accommodate changes more effectively and deliver software in smaller, functional pieces. This flexibility has contributed to Agile's growing popularity in the software industry, as evidenced by surveys such as the KPMG PMI Project Management Survey 2022, which shows that Agile methodologies are becoming the norm for many organizations aiming to improve their project success rates KPMG PMI Survey [9].

3.2 Case Studies and Relevant Examples

Several high-profile case studies and industry reports have driven the shift from traditional methods like Waterfall to Agile. One notable example is Broadcom's adoption of Agile, as detailed in their report, which quantifies the impact of Agile methodologies on software development productivity. Broadcom saw significant improvements in project delivery times and a reduction in defects, highlighting Agile's strengths in iterative development and faster feedback loops in Broadcom Software [5].

Another case study involves Deloitte's application of Agile in government projects, where Agile was implemented in public sector software projects to enhance collaboration and speed of delivery. As per Deloitte's insights, Agile approaches allowed government agencies to provide better services to the public by being more responsive to changing requirements and accelerating delivery timelines Deloitte [10].

Additionally, data from KPMG's PMI Project Management Survey 2022 reveals that Agile project management has increasingly been adopted by organizations looking to tackle the complexities of modern software development. The survey highlights that 79% of organizations have adopted Agile practices, and many have seen improved success rates in managing projects effectively, reflecting a broader trend in the industry where Agile methodologies have become the gold standard for managing dynamic and fast-paced software projects KPMG PMI Survey [9].

The Agile vs. Waterfall debate continues to be relevant in modern software development. Reports like those from Agile Genesis provide valuable insights into the ongoing comparison of Agile and Waterfall, with Agile showing superior success rates in terms of project flexibility and stakeholder satisfaction. According to statistics in Agile Genesis [3], Agile projects have a 64% success rate, compared to only 49% for Waterfall projects, further validating the shift towards more adaptive and responsive project management strategies in the software industry.

4. Dimensions of Success in Software Project Management

4.1 Traditional Metrics: Time, Cost, Scope

The traditional 'iron triangle' of project management—time, cost, and scope—remains a fundamental framework for assessing project success. According to insights from the Project Management Institute (PMI), these dimensions continue to define the foundational principles of effective project delivery, particularly in industries where stability and predictability are essential, such as construction and manufacturing.

Time is a critical factor, as projects must adhere to strict deadlines to ensure timely delivery. Cost management is equally important, requiring financial discipline to stay within allocated budgets. Scope, meanwhile, ensures that the project meets all agreed-upon deliverables. Despite the increasing adoption of more adaptive methodologies, these traditional metrics still provide a reliable benchmark for project success, particularly as organizations grapple with the growing global demand for skilled project professionals [11].

4.2 Expanded Metrics: Stakeholder Satisfaction and Business Value

Modern project management practices have expanded the definition of success to include stakeholder satisfaction and business value. As noted by KPMG in their MPS Survey (2022), organizations with mature project management processes are increasingly shifting their focus toward these broader metrics to ensure long-term success.

Stakeholder satisfaction reflects how effectively a project meets or exceeds the expectations of its stakeholders, fostering stronger relationships and trust. Business value, on the other hand, measures how well the project aligns with and supports the organization’s strategic goals. According to KPMG, organizations that adopt these metrics experience higher levels of success, delivering projects that not only meet immediate goals but also drive sustained value for the organization [9].

5. Key Factors Influencing Quality in Software Projects

5.1 Tools and Technologies

High-quality software projects often rely on advanced tools and technologies to streamline processes and improve outcomes. The Broadcom Agile Impact Report underscores the importance of adopting innovative tools, such as automated testing frameworks and

integrated development environments, in enhancing team efficiency and reducing errors [5].

5.2 DevOps and Continuous Integration

According to Visual-Planning, integrating DevOps practices and continuous integration (CI) frameworks is essential for fostering collaboration and improving quality assurance. Teams that adopt CI tools benefit from faster development cycles and significantly fewer post-deployment issues, as these tools allow for early detection and resolution of potential problems [7].

5.3 Process Standards and Frameworks

Adhering to established standards, such as ISO, or adopting structured methodologies like CMMI plays a critical role in maintaining consistent quality. PMI and Deloitte emphasize that these frameworks are particularly valuable for scaling projects in regulated industries, where quality control is paramount [8] [10].

5.4 Effects of Scaling on Teams and Management

As noted by Agile Genesis, scaling agile teams introduces challenges related to communication and maintaining quality. While small agile teams often achieve high success rates, scaling requires frameworks like SAFe and LeSS to ensure alignment and consistency. Without proper management, scaling efforts can lead to diminishing returns, underscoring the need for structured approaches to growth [3][12].

6. Challenges in Balancing Quality and Success

6.1 Trade-offs Between Speed and Quality

Balancing the need for speed with quality assurance is a common challenge in dynamic industries. According to Hygger, many companies successfully address this by employing techniques like minimum viable products (MVPs), which allow for faster market delivery while managing expectations for feature completeness. This approach has been shown to enhance customer retention rates and improve responsiveness to market demands [13].

6.2 Risk Management in Dynamic Environments

Knowledge Hut highlights that proactive risk management is crucial in environments characterized by frequent changes. Agile methodologies, with their iterative and incremental cycles, enable teams to identify and address risks early, reducing unforeseen challenges by up to 40% compared to traditional approaches. This proactive approach ensures greater project resilience and adaptability [14].

7. Hybrid and Adaptive Methodologies

7.1. Waterfall-Agile and Scrumfall: Their Definition and Applicability

In project management, professionals aim to forecast progress, identify potential challenges, and design processes that will guide the achievement of project objectives. As they gain experience, project managers refine their expertise in selecting and tailoring methodologies to ensure timely, within-scope, and budget-compliant project delivery. Over time, this ongoing learning has led to the development of hybrid project management approaches, which combine elements of multiple methodologies to create more adaptable frameworks. This paper will explore the various project management methodologies, demonstrate how they can be integrated into hybrid models, and explain the benefits of considering such an approach for your next project.

Types of Project Management Methodologies

Waterfall Method

The Waterfall model is a linear and sequential approach to project management, where project phases are completed in a fixed, predetermined order. This method is widely used in industries requiring detailed upfront planning and stable project requirements, such as construction or manufacturing. It allows for clear documentation, resource allocation, and budget monitoring, making it a reliable choice for projects with minimal changes. However, the inflexibility of the Waterfall approach may be unsuitable for projects with evolving or unclear requirements, necessitating the use of more adaptive methodologies such as Agile or hybrid approaches [15].

Agile Method

Agile project management emphasizes flexibility, rapid iterations, and continuous stakeholder feedback. By breaking projects into smaller, manageable components or sprints, Agile allows teams to adapt to shifting requirements while maintaining focus on

delivering value. This approach fosters collaboration and cross-functional teamwork, which helps ensure that projects stay aligned with client expectations. Agile is especially effective in environments with frequent changes and where quick delivery of functional elements is prioritized [16].

Scrum Framework

Scrum is a popular Agile methodology, particularly in software development, that focuses on iterative progress through predefined roles and regular cycles known as sprints. Unlike traditional Agile, which may release deliverables only at the end of an iteration, Scrum allows for incremental launches, ensuring quicker feedback and adaptation. The Scrum framework is highly suited to projects where rapid development and market responsiveness are essential. This method enables teams to address emerging challenges more swiftly by delivering partial but valuable components early and regularly.

Each of these methodologies offers unique advantages and can be adapted or blended based on project needs and the environment. As project requirements evolve, hybrid approaches are increasingly favored for their ability to combine the strengths of multiple frameworks to deliver better outcomes. [17]

7.2 Advantages and Disadvantages of Hybrid Methodologies

Hybrid project management blends elements from both Waterfall and Agile methodologies, allowing for a tailored, adaptable approach to project execution. This method provides several benefits while also requiring careful consideration of several factors to ensure its effectiveness in a given project context. [18]

The hybrid project management approach, while offering significant advantages, also presents several challenges that project managers must navigate to ensure success. One of the primary difficulties is the complexity of combining methodologies like Agile and Waterfall, which have very different processes and tools. The integration of these approaches requires a deep understanding of both frameworks to balance their distinct characteristics effectively. Flexibility is another crucial aspect of the hybrid approach, but it can also become a pitfall. Successful implementation requires all team members and stakeholders to be ready for changes in plans, which can be difficult if they are not accustomed to this level of adaptability. This means that both teams and stakeholders must be educated and prepared for potential adjustments throughout the project lifecycle. If stakeholders are unfamiliar with the hybrid process, it can create confusion and hinder progress.

Moreover, there is often a clash between the structured, rigid processes of Waterfall and the flexible, iterative nature of Agile. These contrasting mindsets can cause friction within the team and disrupt workflow if not managed properly. The hybrid approach also demands

high levels of communication and collaboration, especially when teams with different working styles need to come together. This requires developing clear systems for communication, reporting, and feedback to ensure everyone remains aligned with the project goals.

Finding the right balance between control and autonomy is another ongoing challenge. While Waterfall emphasizes control, Agile encourages autonomy, and integrating these two aspects can be difficult. Resistance to change is another hurdle that teams must overcome, particularly when individuals are used to a more traditional approach or are unfamiliar with Agile methods. Managing this resistance and fostering a culture open to change is essential for a successful hybrid project. [18] [19]

7.3 Use Cases for Hybrid Approaches

Hybrid project management methodologies have become increasingly popular across industries, particularly in large and medium-sized organizations seeking adaptable approaches for managing complex projects. According to the State of Agile report, nearly half of large companies (49%) and medium-sized companies (45%) now adopt hybrid project management models, incorporating a combination of methodologies such as Agile, DevOps, Waterfall, Lean, Spiral, and iterative approaches. This shift allows organizations to tailor their software development life cycle (SDLC) to meet the specific demands of each project.

The hybrid approach is particularly effective when combining the strengths of Agile and Waterfall methodologies. Agile is well-suited for complex and uncertain projects that demand flexibility, enabling teams to respond quickly to changes and evolving requirements. Waterfall, on the other hand, works best for projects with well-defined requirements and clear processes, where a structured, linear approach is necessary. However, implementing Agile in large organizations can be challenging, as deeply ingrained traditional processes often create barriers. The larger the organization, the harder it becomes for Agile teams to operate effectively within a rigid framework. To make Agile work, organizations must grant teams a level of autonomy and ensure that team members are open to more flexible ways of working.

In such cases, a hybrid approach offers a solution, allowing organizations to retain their existing processes while benefiting from the flexibility of Agile. By combining the structure of Waterfall with the adaptability of Agile, hybrid models can help organizations optimize project outcomes, even in large-scale environments with established processes. This approach is especially beneficial for projects with tight deadlines, where delivering a functional product quickly is crucial. The hybrid model ensures that projects stay on track and that products are delivered on time, without sacrificing quality or functionality.

For example, consider a website launch project. The planning phase might begin with the Waterfall methodology, where comprehensive research, strategy development, and client requirements gathering are conducted. This phase provides a solid foundation for the project. Following this, the UX phase is handled using Waterfall processes to ensure that stakeholder feedback is incorporated before moving forward.

As the project progresses to the UI phase, the approach shifts to Agile. In this phase, iterative sprints allow for continuous feedback and quick adjustments. Once a few UI pages are approved by stakeholders, they move into development and testing, also managed through Agile sprints. This iterative process ensures continuous progress, with each phase overlapping and evolving based on feedback from the previous stage.

Another example can be seen in large-scale organizations with rigid processes. In such cases, the hybrid approach allows for the integration of Agile's iterative development with Waterfall's detailed planning, offering a balance of predictability and flexibility. This hybrid method helps address dynamic requirements and evolving scopes, enabling organizations to maintain structured planning while remaining responsive to feedback. In both examples, the hybrid approach optimizes project management by ensuring that the project is both well-planned and adaptable, ultimately delivering timely results without compromising quality. [17] [20] [21]

8. Impact of Modern Technologies and AI

8.1 Use of Artificial Intelligence in Estimating and Planning

In the last couple of years, the use of Artificial Intelligence across all fields has increased significantly. Software project management is a task concerned with delivering software on a constrained budget and a limited timeframe, so it is not surprising that AI has been employed to try and solve some of the challenges associated with software development.

A key aspect when managing any project, especially a software-based one, is planning. As Liyan Song and Leandro L.Minku [22] state in their paper, software project scheduling (SPS) involves organizing and allocating tasks, estimating effort, and determining employee resources while considering dependencies and constraints. Given the complexities involved, including skill requirements, task dependencies, and the need to balance costs and durations, manually creating an optimal schedule can be a daunting task.

As such, AI approaches can assist project managers by automating the allocation of resources and optimizing schedules based on predefined objectives, such as minimizing cost or duration.

8.2 Trends in Software Management Practices

Artificial Intelligence (AI) is increasingly being employed in Agile project management to enhance efficiency and decision-making processes. By automating repetitive tasks, such as effort estimation and risk prediction [23], AI enables project teams to focus on higher-value activities, leveraging project analytics to streamline decision-making frameworks. Furthermore, AI-powered tools are transforming risk management by providing automated assessment and prioritization mechanisms, effectively addressing the limitations of traditional manual approaches that rely heavily on individual expertise [23].

Recent data from Project.co, a company behind a project management software with the same name, indicates that the integration of Artificial Intelligence (AI) into project management is becoming increasingly prevalent [7], with 45% of professionals incorporating AI into their workflows. Among these users, 35% report consistent utilization, while 64% engage with AI tools intermittently. The primary applications of AI in this domain include idea generation, content creation, task automation, and decision-making support (45%). Despite these advancements, a significant portion(55%) have yet to adopt AI, primarily due to a lack of awareness or understanding.

Looking forward, there is a strong inclination towards AI adoption, with most respondents anticipating its future use in project management, and predicting a substantial impact on the industry. Notably, 84% of current AI users have experienced enhanced project efficiency [24], underscoring AI's potential to revolutionize project management practices.

Early adopters of AI in managing software projects, according to Elizabeth Harrin [25], have observed substantial benefits, with 41% reporting significant enhancements in project delivery and 28% acknowledging that AI augments their skill sets, particularly in methodology and life-cycle management. These trends underscore AI's transformative potential in automating routine tasks, enhancing decision-making, and improving overall project outcomes.

9. Quality Practices and Case studies in Software Project Management

9.1 Correlation Between Quality Practices and Project Success

The correlation between quality management practices and project success in software project management has been extensively studied, revealing a significant positive relationship [26]. Implementing a comprehensive quality management plan, which includes systematic planning, assurance, and control measures, is associated with higher project

success rates. This correlation underscores the importance of integrating quality management into project workflows to enhance outcomes.

Additionally, a comprehensive correlation analysis between critical success factors (CSFs) [27] and project success indicates positive associations between the majority of these factors and successful project outcomes. This finding emphasizes the importance of identifying and managing CSFs to improve the likelihood of project success.

9.2 Insights from Industry Case Studies

The study conducted by Broadcom [5], as detailed in their publication "The Impact of Agile," provides a comprehensive analysis of statistics and trends in software project management, with a focus on Agile methodologies. Using anonymized data from over 160,000 projects and 50,000 Agile teams, the research highlights the Software Development Performance Index (SDPI), which evaluates projects across four key dimensions: Quality, Productivity, Predictability, and Responsiveness. The study demonstrates significant correlations between specific Agile practices and improved project outcomes.

For instance, teams with high stability (where team members remain consistent across quarters) exhibited up to 60% better productivity and responsiveness. Similarly, dedicating team members to a single project yielded nearly double the throughput compared to less focused teams. Another critical finding is the impact of work-in-process (WiP) control. Teams with low WiP achieved four times better quality outcomes, though excessive reduction in WiP could negatively affect productivity. Furthermore, the adoption of specific Agile methodologies, such as Full Scrum and Lightweight Scrum, was associated with higher performance, with Full Scrum delivering up to 250% better quality outcomes. Interestingly, two-week iterations were found to balance performance across all dimensions, outperforming both shorter and longer iterations.

Another case study involving 21 IT professionals [28], conducted within a large North American financial institution, reveals critical insights into the determinants of software project success and failure. A key finding is that customer and user involvement throughout the project lifecycle is paramount, with higher levels of engagement strongly correlating with improved perceptions of success by both management and developers. Developers identified additional critical success factors, such as a well-defined project scope and realistic customer expectations, emphasizing their importance in maintaining project clarity and feasibility.

Conversely, projects that lacked a committed sponsor at the outset or experienced sponsor disengagement during development exhibited significantly reduced success rates, particularly from the developers' perspective. The research also highlights the detrimental impact of incomplete or poorly defined requirements at project initiation, which developers perceive as a major obstacle to effective execution. These findings underscore the necessity

of early-stage risk identification, robust management support, and active stakeholder collaboration to enhance software project success rates and address disparities in stakeholder perceptions of project outcomes.

10. Conclusions and Perspectives

Hybrid project management methodologies are increasingly being adopted across industries, particularly by larger organizations seeking to enhance their ability to manage complex and dynamic projects. The hybrid model effectively merges the predictability of traditional methodologies, such as Waterfall, with the adaptability of Agile, creating a balanced framework that can be tailored to meet the specific demands of each project.

As highlighted in the *State of Agile* report. [16], a significant proportion of large and medium-sized companies (nearly half) have integrated hybrid approaches into their operations, recognizing the value of customizing their project management practices to align with the unique needs of their projects terms of effectiveness, hybrid methodologies are particularly advantageous for projects characterized by evolving requirements. For instance, a project that begins with a clear, well-defined scope (typical of the Waterfall approach) can transition into iterative, Agile-driven phases as the project progresses. This transition allows for the flexibility needed to respond to changing conditions, providing ongoing adaptation in the development process (Morris, 2023). Such adaptability is crucial for projects in environments where rapid change is the norm and immediate feedback is necessary. By combining structured planning in the initial stages with iterative development through Agile sprints, organizations can strike a balance between control and flexibility, optimizing project performance and improving stakeholder satisfaction.

The ease of implementing hybrid methodologies, however, varies significantly depending on an organization's size, culture, and existing project management practices. In large organizations, the integration of Agile practices can present significant challenges due to deeply ingrained traditional processes. As organizations scale, the barriers to adopting Agile grow, often making it difficult to incorporate its flexible, iterative nature within established, rigid frameworks. In such contexts, hybrid methodologies provide an effective solution by enabling teams to retain control over processes while also benefiting from Agile's inherent flexibility. Successful implementation of hybrid approaches generally requires organizational buy-in, training, and a shift in mindset to embrace autonomy and iterative workflows. [29]

When correctly implemented, the impact of hybrid methodologies on project outcomes is overwhelmingly positive. These methodologies provide the dual advantage of ensuring timely delivery without compromising functionality or quality. One of the key strengths of hybrid approaches is their ability to manage both short-term project objectives and long-

term goals. For instance, in large-scale projects with tight deadlines, such as product launches, the hybrid model ensures rapid movement through the different phases (Waterfall for initial planning and Agile for subsequent development and testing) thereby reducing the overall project timeline while maintaining high standards for the final product. In conclusion, hybrid project management methodologies offer a highly adaptable, structured, and efficient approach to managing complex projects. While they are highly effective, particularly in environments that require flexibility, their implementation can be challenging in large organizations with rigid systems. Success with hybrid methodologies is largely dependent on the level of team autonomy, organizational culture, and the willingness to adapt existing project structures. When applied effectively, however, hybrid methodologies can significantly enhance project outcomes by combining the predictability of Waterfall with the iterative, responsive characteristics of Agile, enabling organizations to deliver successful projects in dynamic environments.

Acknowledgment

We recognize the contribution of ChatGPT in refining the linguistic and academic quality of this paper, as well as in supporting reference organization.

References

[1] Kasia Kowalska, “The great dilemma. Agile or waterfall?”, Boldare, 2019, Retrieved from https://www.boldare.com/blog/agile-vs-waterfall, Last Accessed at: 13.03.2025

[2] Ciupe, A., Ionescu, R., Meza, S., & Orza, B. (2018). Towards agile integration within higher education: A systematic assessment. BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 9(3), 69-87.

[3] Ernesto Custodio, “Agile vs. Waterfall: Comparing Success Rates in Project Management”, AgileGenesis, Retrieved from https://www.agilegenesis.com/post/agile-vs-waterfall-comparing-success-rates-in-project-management Last Accessed at: 13.03.2025

[4] Quixy, “Important Project Management Statistics for 2025 and beyond”, Retrieved from https://quixy.com/blog/important-project-management-statistics/ Last Accessed at: 13.03.2025

[5] Broadcom. (n.d.). *The impact of Agile quantified.* Retrieved from https://docs.broadcom.com/doc/the-impact-of-agile-quantified Last Accessed at: 13.03.2025

[6] Zippia. (n.d.). *Agile statistics.* Retrieved from https://www.zippia.com/advice/agile-statistics/ Last Accessed at: 13.03.2025

[7] Visual Planning. (n.d.). *Project management statistics.* Retrieved from https://www.visual-planning.com/en/blog/project-management-statistics Last Accessed at: 13.03.2025

[8] Project Management Institute. (2021). *Talent Gap Report 2021.* Retrieved from https://www.pmi.org/-/media/pmi/documents/public/pdf/learning/career-central/talent-gap-report-2021-finalfinal.pdf Last Accessed at: 13.03.2025

[9] Deloitte. (n.d.). *Agile in government.* Retrieved from https://www2.deloitte.com/content/dam/insights/us/articles/3897_Agile-in-government/DUP_Agile-in-Government-series.pdf Last Accessed at: 13.03.2025

[10] KPMG. (2022). *PMI project management survey 2022.* Retrieved from https://assets.kpmg.com/content/dam/kpmg/cy/pdf/2023/kpmg_pmi_project_management_survey_2022.pdf Last Accessed at: 13.03.2025

[11] Thesing, T., Feldmann, C., & Burchardt, M. (2021). Agile versus waterfall project management: decision model for selecting the appropriate approach to a project. Procedia Computer Science, 181, 746-756.

[12] Johnivan J.R. (2024). *Agile vs Waterfall Methodology: Differences & How to Choose.* Project Management Articles, Retrieved from https://project-management.com/agile-vs-waterfall/ Last Accessed at: 13.03.2025

[13] Hygger. (n.d.). *Why Agile is so popular in project management.* Retrieved from https://hygger.io/blog/why-agile-is-so-popular-in-project-management/ Last Accessed at: 13.03.2025

[14] KnowledgeHut. (n.d.). *State of Agile.* Retrieved from https://www.knowledgehut.com/blog/agile/state-of-agile Last Accessed at: 13.03.2025

[15] Garousi, V., Tarhan, A., Pfahl, D., Coşkunçay, A., & Demirörs, O. (2019). Correlation of critical success factors with success of software projects: an empirical investigation. Software Quality Journal, 27, 429-493.

[16] StarAgile. (n.d.). *State of Agile 2024: Insights, trends, and key findings.* Retrieved from https://staragile.com/blog/state-of-agile Last Accessed at: 13.03.2025

[17] Float. (n.d.). *Hybrid project management.* Retrieved from https://www.float.com/resources/hybrid-project-management Last Accessed at: 13.03.2025

[18] Simplilearn. (n.d.). *What is hybrid project management?* Retrieved from https://www.simplilearn.com/what-is-hybrid-project-management-article Last Accessed at: 13.03.2025

[19] TeamGantt. (n.d.). *Hybrid approach to project management.* Retrieved from https://www.teamgantt.com/waterfall-agile-guide/hybrid-approach Last Accessed at: 13.03.2025

[20] Business Map. (n.d.). *Hybrid project management.* Retrieved from https://businessmap.io/blog/hybrid-project-management Last Accessed at: 13.03.2025

[21] Bernsen, R. (2022, April 25). *What is hybrid project management?* OpenProject. Retrieved from https://www.openproject.org/blog/what-is-hybrid-project-management/ Last Accessed at: 13.03.2025

[22] Project.co, "The Use of AI in Project Management Statistics 2024",2024, Retrieved from https://www.project.co/ai-statistics/ Last Accessed at: 13.03.2025

[23] Song, L., & Minku, L. L. (2023). Artificial intelligence in software project management. In Optimising the software development process with artificial intelligence (pp. 19-65). Singapore: Springer Nature Singapore.

[24] Project Management Institute. (2023). *Global project management job trends 2023*. Retrieved from https://www.pmi.org/learning/careers/global-job-trends-2023 Last Accessed at: 13.03.2025

[25] Crawford, T., Duong, S., Fueston, R., Lawani, A., Owoade, S., Uzoka, A., ... & Yazdinejad, A. (2023). AI in software engineering: a survey on project management applications. arXiv preprint arXiv:2307.15224.

[26] Procaccino, J. D., Verner, J. M., Overmyer, S. P., & Darter, M. E. (2002). Case study: factors for early prediction of software development success. Information and software technology, 44(1), 53-62.

[27] Procaccino, J. D., & Verner, J. M. (2006). Software project managers and project success: An exploratory study. Journal of Systems and Software, 79(11), 1541-1551.

[28] Elizabeth Harrin, "57 AI in Project Management Statistics", RGPM, Retrieved from https://rebelsguidetopm.com/ai-in-project-management-statistics/ Last Accessed at: 13.03.2025

[29] Abbas, J. (2016). Quintessence of traditional and agile requirement engineering. Journal of Software Engineering and Applications, 9(3), 63-70.

Bibliography

AGRAWAL A., SINGH V., FISCHER M. *LeanAI: A method for AEC practitioners to effectively plan AI implementations*. arXiv preprint arXiv:2306.16799. ISSN 2331-8422. 2023

BENTO S., PEREIRA L., GONÇALVES R., DIAS Á., COSTA R. L. D. *Artificial intelligence in project management: systematic literature review*. International Journal of Technology Intelligence and Planning, ISSN 1740-2840, 143-163. 2022

COBB C. G. *The project manager's guide to mastering Agile: Principles and practices for an adaptive approach*. John Wiley & Sons. ISBN 9781118085950. 2011

COBB C. G. *Making sense of agile project management: balancing control and agility*. John Wiley & Sons. ISBN 9781118085950. 2011

COBB C. G. *From quality to business excellence*. Quality Press. ISBN 9781118085950. 2002

DEVARAJ S., VAIDYANATHAN G., MISHRA A. N. *Effect of purchase volume flexibility and purchase mix flexibility on e-procurement performance: An analysis of two perspectives*. Journal of Operations Management, ISSN 0272-6963, 509-520. 2012

FAIR J. *Agile versus Waterfall: approach is right for my ERP project?* Paper presented at PMI® Global Congress 2012—EMEA, Marsailles, France. Newtown Square, PA: Project Management Institute. 2012

FOSSO WAMBA S., QUEIROZ M. M., GUTHRIE C., BRAGANZA A. *Industry experiences of artificial intelligence (AI): benefits and challenges in operations and supply chain management*. Production planning & control, ISSN 1366-5871, 1493-1497. 2022

MISHRA A. N., DEVARAJ S., VAIDYANATHAN G. *Capability hierarchy in electronic procurement and procurement process performance: An empirical analysis*. Journal of Operations Management, ISSN 0272-6963, 376-390. 2013

MEZIANE F., VADERA S. *Artificial intelligence in software engineering: current developments and future prospects*. Artificial intelligence applications for improved software engineering development: New prospects, ISBN 9781605667584, 278-299. 2010

MÜLLER R., LOCATELLI G., HOLZMANN V., NILSSON M., SAGAY T. *Artificial intelligence and project management: Empirical overview, state of the art, and guidelines for future research*. Project Management Journal, ISSN 8756-9728, 9-15. 2024

QUEIROZ M. M., WAMBA S. F. *Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA*. International Journal of Information Management, ISSN 0268-4012, 70-82. 2019

RUSSELL R. S., TAYLOR B. W. *Operations and supply chain management*. John Wiley & Sons. ISBN 978-1-119-57765-2. 2019

SANDERS N. R., WOOD J. D. *The Humachine: Humankind, machines, and the future of Enterprise*. Routledge. ISBN 9781138571341. 2019

SANDERS N. R., BOONE T., GANESHAN R., WOOD J. D. *Sustainable supply chains in the age of AI and digitization: research challenges and opportunities*. Journal of Business logistics, ISSN 0735-3766, 229-240. 2019

SAVIO R. D., ALI J. M. *Artificial intelligence in project management & its future*. Saudi Journal of Engineering and Technology, ISSN 2415-6264, 244-248. 2023

SHAYDULIN R., SYBRANDT J. *To agile, or not to agile: A comparison of software development methodologies*. arXiv preprint arXiv:1704.07469. ISSN 2331-8422. 2017

VAIDYANATHAN G. *Project management: process, technology, and practice*. Pearson Higher Ed. 2013

VAIDYANATHAN G., DEVARAJ S., D'ARCY J. *Does security impact e-procurement performance? Testing a model of direct and moderated effects*. Decision Sciences, ISSN 1540-5915, 437-458. 2012

VAIDYANATHAN G., MAUTONE S. *Security in dynamic web content management systems applications*. Communications of the ACM, ISSN 1557-7317, 121-125. 2009

VAIDYANATHAN G., DEVARAJ S. *The role of quality in e-procurement performance: An empirical analysis*. Journal of Operations Management, ISSN 1873-1317, 407-425. 2008

VAIDYANATHAN G. *A framework for evaluating third-party logistics*. Communications of the ACM, ISSN 1557-7317, 89-94. 2005

VAIDYANATHAN G., DEVARAJ S. *A five-factor framework for analyzing online risks in e-businesses*. Communications of the ACM, ISSN 1557-7317, 354-361. 2003

VEIGA A. P. *Project success in Agile development projects*. arXiv preprint arXiv:1711.06851. ISSN 2331-8422. 2017

WAMBA S. F. *Impact of artificial intelligence assimilation on firm performance: The mediating effects of organizational agility and customer agility*. International Journal of Information Management, ISSN 1873-4707. 2022

WAMBA S. F., AKTER S., EDWARDS A., CHOPIN G., & GNANZOU D. *How 'big data' can make big impact: Findings from a systematic review and a longitudinal case study*. International journal of production economics, ISSN 1873-7579, 234-246. 2015

WAMBA S. F., GUNASEKARAN A., AKTER S., REN S. J. F., DUBEY R., & CHILDE S. J. *Big data analytics and firm performance: Effects of dynamic capabilities*. Journal of business research, ISSN 1873-7978, 356-365. 2017

THE TRADE-OFF BETWEEN PERFORMANCE, COST AND ENVIRONMENT IMPACT IN SOFTWARE DEVELOPMENT

Andrei NĂPRUIU[1]
Flavius PETRACHE[2]
Larisa Elena FLOREA[3]
Ștefania Maria FÎNTÎNĂ[4]
Mădălina-Elena TIȚA[5]
Costin-Anton BOIANGIU[6]

Abstract

In today's world, modern software development requires more and more to balance performance, cost, and environment impact. We are used with traditional engineering practices, that have emphasized speed and rapid delivery. But the growing energy consumption and carbon footprint of software systems has made sustainability a pressing concern. The aim of this paper is to examine the trade-offs among these dimensions, performance, cost, and environmental, by defining relevant metrics and by conducting an empirical analysis based on the Energy-Languages dataset. The results show significant differences in energy consumption and execution efficiency across programming language categories, with interpreted languages exhibiting substantially higher operational costs and emissions. A Pareto analysis further indicates that modern compiled languages can achieve favorable compromises across all three dimensions. Overall, the findings demonstrate that performance, cost efficiency, and sustainability are not inherently conflicting goals, but can be jointly optimized through informed design choices.

For the scope of this paper, we will consider software engineering and software development as being the same and therefore interchangeable.

Keywords: software development, trade-off between performance, cost and ecological impact, language programing, rust, machine learning.

JEL Classification: D61, D24, L19, Q51.

[1] Department of Computer Science, National University of Science and Technology POLITEHNICA Bucharest, Romania
[2] Department of Computer Science, National University of Science and Technology POLITEHNICA Bucharest, Romania
[3] Department of Computer Science, National University of Science and Technology POLITEHNICA Bucharest, Romania
[4] Department of Computer Science, National University of Science and Technology POLITEHNICA Bucharest, Romania
[5] Phd Candidate, Automation and Computers Doctoral School, National University of Science and Technology POLITEHNICA Bucharest, Romania, email address madalina.tita@stud.etti.upb.ro
[6] Corresponding author, Professor in the department of Computer Science in the Faculty of Automatic Control and Computer Science, National University of Science and Technology POLITEHNICA Bucharest, Romania. Email address costin.boiangiu@upb.ro

1. Introduction

Software development is an increasingly challenging domain, as today's projects are created under three main demands: **Performance** (speed of execution, scalability, and responsiveness to user requests), **Cost** (financial and time management), and last but not least, **Environmental Impact** (energy usage and carbon emissions).

As a result of these competing requirements, the software engineers make crucial efforts in achieving a balance between these three factors (performance, cost, and environment). The main problem is that software engineers have always viewed the optimization of one factor as negatively impacting the other two factors.

In the race to build software faster and cheaper, developers are often pushed into uncomfortable compromises. Rapid, low-cost development frequently relies on heavy frameworks, inefficient abstractions, or even hardware-based "brute force" solutions.

Although these approaches may speed up delivery, often they come at a hidden cost: reduced performance efficiency and increased energy consumption. Not surprisingly, even the highly optimized, performance-driven software solutions can demand more servers, more memory, and more computational power, increasing expenses and environmental impact. This reality reveals an important truth: improving an application's responsiveness or capabilities is no longer just a technical challenge, but also an economic and ecological one.

In recent years, sustainability has become a real concern and has started to reshape how these trade-offs are understood. Not long ago, environmental impact barely was considered an important factor when talking about software design. The primary goals were simple: finish features quickly, meet deadlines, and scale, when necessary, under the assumption that hardware resources were abundant and inexpensive. Today, that assumption no longer valid.

Another aspect to consider when talking about software developing is the manufacturing price of memory modules. For example, in 2025, the rapid expansion of artificial intelligence (AI) research and the deployments of large-scale data centers had a clear impact on global RAM prices. As memory manufacturers shifted production toward high-bandwidth and server-grade RAM needed for AI workloads, the supply for standard DRAM and DDR5 decreased. As a result, RAM prices increased rapidly, by roughly 80% to over 150% year-over-year, with some consumer and enterprise memory modules nearly doubling in cost within few months.

Due to the fact that data centers consume vast amounts of electricity, digital services have started to contribute to global carbon emissions, which makes the environmental footprint of software is impossible to ignore. As a result, the tech industry is beginning to recognize

that energy efficiency in code and system architecture is a core aspect of responsible engineering.

This growing awareness has started to challenge the longstanding belief that "green" software must inevitably be slower, weaker, or more expensive. Many software organizations are now demonstrating that thoughtful design choices can deliver speed, scalability, and sustainability at the same time and even the same price. By using cleaner code, efficient algorithms, and well-designed architectures, they have improved performance and reduced power consumption.

The old mindset of treating hardware as limitless is being replaced by a more careful evaluation of trade-offs, where every improvement is weighed not only in milliseconds or user convenience, but also in financial and environmental terms. This makes it difficult to evaluate, since the beginning, if adding an extra feature, a marginal speed gain, or an extreme optimization is worth the additional energy use and cost.

In this context, the aim of this paper is to explore the delicate balance between performance, cost, and environmental impact in modern software development. It analyses how each of these factors can be defined and measured in real situations, and why they cannot be treated as secondary concerns. Through concrete examples and strategies, the goal of this paper is to show how software teams, and those who educate them, can pursue solutions that are not only technically impressive, but also economically sensible and environmentally responsible.

2. Concepts and Metrics

2.1. Software Performance

Software performance refers to how efficiently and how quickly a software system carries out its functions. In general, performance is evaluated using a set of quantitative metrics:

• **Response time** (latency): the time required for the system to respond to a request (for example, the loading time of a web page or the execution time of a function).

• **Throughput**: the number of operations or transactions the system can process within a given unit of time (e.g., requests per second).

• **Resource utilization**: the level of computing resources consumed during execution: CPU, memory, network bandwidth, disk space, and so on. Efficient performance implies careful use of available resources; for example, ISO 25010 defines performance efficiency as "the ability of software to provide appropriate performance relative to the number of resources used". Code that achieves very short execution times but consumes excessive amounts of CPU or memory may be considered inefficient from a resource perspective.

In practice, developers often focus on performance optimization to ensure low response times and smooth user interaction. For instance, reducing latency from 100ms to 50ms can improve the user experience. However, the real benefit of such highly aggressive optimizations must be weighed against their cost and energy impact. It is important to note that in many cases, improving performance through better algorithms or code optimizations also brings environmental benefits, as more efficient code performs fewer unnecessary operations and may consume less energy. On the other hand, increasing performance through brute-force methods (such as running the processor at higher frequencies or using more cores) can reduce latency but also increases energy consumption and heat generation.

Performance metrics are usually measured using throughput by simulating a large number of concurrent users, and CPU/RAM usage through resource monitoring tools. A good practice is to define performance requirements (non-functional requirements) early in the specification phase, for example, "the system must respond to 95% of requests in under 200ms." At the same time, performance should be aligned with user behavior and business needs; in some cases, pursuing the best possible performance is not justified if the improvement is not noticeable to users or relevant to business objectives.

2.2. Cost of Software Development

The cost of software development refers to the total amount of financial, temporal, and human resources required to design, implement, test, deploy, and maintain a software system throughout its lifecycle. In its simplest form, **software cost** can be understood as the **sum of development effort and supporting material or infrastructural expenses**. Accurately defining and measuring this cost is a central concern in software engineering, as it directly influences planning, budgeting, and project feasibility assessments [1], [2].

One of the most widely used approaches to software cost is in terms of development effort, typically measured in *person-hours* or *person-months*. This metric captures the cumulative labor contributed by developers, testers, and other technical staff calculated hourly or monthly. To systematically estimate effort, we proposed several parametric cost estimation models. Among them, the **Constructive Cost Model** (COCOMO) is considered to be one of the most influential ones. Originally introduced by Boehm, COCOMO estimates the effort as a function of software size and a set of cost drivers related to product, personnel, platform, and project attributes [3]. Later extensions such as COCOMO II incorporate, as well, modern development practices, reuses, and evolving system requirements, making the model applicable to contemporary software projects [4].

The concept of **software size measurement** is closely related to effort estimation, this serves as a primary input for many cost models. Traditional approaches rely on **Source Lines of Code** (SLOC) as a quantitative measure of system size. Although SLOC is a straightforward method of computation after implementation, it is language-dependent and sensitive to coding style, which limits its usefulness during early project stages [5]. To

address these limitations, we introduced alternative metrics such as **Function Points** (FP). FP estimate software size based on the number and the complexity of externally visible functionalities, enabling cost estimation earlier in the development process and independently of the programming language used [6]. Additionally, software cost includes **infrastructure and operational expenses** incurred during the development and the deployment phases. These costs may involve expenses for hardware acquisition for infrastructure that can become significant for large-scale or long-running systems and therefore they are considered an integral part of overall software cost [2].

Another important component of the software cost is related to quality assurance and maintenance activities. Empirical studies consistently show that a substantial part of the total lifecycle cost is spent after initial delivery, covering activities such as defect correction, system adaptation, and functional enhancement [7]. Poor design decisions or insufficient testing during early phases may reduce short-term costs but often lead to increased maintenance costs and higher long-term expenditure. As a result, cost assessment must account for both initial development and post-deployment phases.

We have to take into consideration that software cost is not always measured or monitored the same. From the software project management perspective, software cost is monitored using a variety of project tracking metrics, such as allocated versus actual budget, effort burn-down charts, and time-tracking reports.

However, in academic contexts, software cost may be analyzed from a qualitative perspective, for example taking into consideration system complexity or architectural decisions, which can serve as indicators of future implementation and maintenance effort [1].

In summary, the cost of software development has should factor in development effort, size-based metrics, infrastructure expenses, and maintenance costs. A precise definition and systematic measurement of these components are essential for reliable estimation of cost and informed decision-making in software engineering projects.

2.3. The ecological impact of software

Green Software is an efficient software designed, developed, deployed, and maintained to minimize energy consumption and environmental impact by cultivating faster, higher-quality systems [8]. This concept includes not only the energy consumed by computers and servers when running applications and services, but also the hardware required to support them. The production, use, and disposal of these devices involve material resources and energy and ultimately generate electronic waste. In simple terms, software sustainability describes how much energy and carbon are required for software to exist and to operate over time, as well as the extent to which it contributes to the overall digital environmental footprint.

Green software is considered to be an emerging discipline, also called "sustainable software". Several aspects of green software include optimizing software performance, reducing hardware requirements, extending device lifecycles, and lowering greenhouse gas (GHG) emissions associated with computing tasks [8].

2.4. Concepts and metrics

There are several key concepts and metrics that can be used to measure the ecological impact of software. We will address just the ones that we consider the most relevant.

Energy consumption represents the amount of electrical energy required by a hardware to run a software application and is usually measured in joules (J) or kilowatt-hours (kWh). In practice, energy usage is often related to a specific operation, such as the energy consumed per request or transaction. Measuring the exact energy consumption of a software application is challenging, but modern systems provide tools that help estimate it.

These measurements can be obtained either through external hardware devices or through software interfaces exposed by the operating system or processor. Such measurements allow developers to better understand how much energy their software consumes during execution and to identify opportunities for optimization [9].

Carbon footprint (CO2 equivalent) represents the greenhouse gas (GHG) emissions associated with the energy consumed by a software, and is usually expressed in terms of CO2 production. This metric translates energy consumption into climate impact by taking into account the carbon intensity of the energy source. For example, 1 kWh generated from coal produces significantly more CO2 than 1 kWh generated from renewable sources.

To help better calculate this factor, Green Software Foundation (GSF) proposed a metric called Software Carbon Intensity (SCI), which measures the rate of carbon emissions per functional unit delivered by a software. From a functional standpoint, SCI expresses how many grams of CO2 are emitted for a specific operation, transaction, or other relevant unit of work/action inside the software. The general SCI formulation considers the energy consumed by the software and the carbon intensity of that energy, relative to a defined functional unit [10].

A real-world example of industrial adoption of this metric is provided by the financial institution Intesa Sanpaolo, which, together with NTT Data, implemented an IT energy monitoring solution based on GSF-recommended indicators namely total CO2 emissions (CO2eq) and SCI. Continuous monitoring of these metrics enables the organization to accurately assess the carbon footprint of its software systems and identify optimization opportunities [10][8].

Software energy efficiency represents the ratio between the performance achieved (that is, the amount of "useful work" performed by the software) and the energy consumed to

achieve it. It can be expressed, for example, as the number of operations executed per joule of energy, similarly to the concept of performance per watt used in hardware.

A software system is considered more energy efficient if it performs the same task using less energy. For example, if application A processes 100 web requests using 50 J, while application B processes the same 100 requests using 100 J, application A has twice the energy efficiency of application B.

Improving energy efficiency often involves optimizing performance through better algorithms and more efficient code, as well as smarter resource management. This ensures that hardware does not waste energy by remaining idle unnecessarily or by performing redundant computations. In practice, energy efficiency can be improved through techniques such as avoiding busy-waiting, coalescing tasks to keep hardware components efficiently utilized, and reducing algorithmic complexity, all of which led to more useful work per unit of energy consumed

Hardware footprint and electronic waste (e-waste) are harder to define and therefore to measure because they address the situation when a software is not depended on a particular hardware and could be used on a variety of electronic devices. In this situation, the software companies are not bound to take into consideration the hardware cost when updating or upgrading their software.

Software affects the environment not only through the energy it consumes during execution, but also through the way it influences hardware usage over time. Applications that require increasingly powerful computational resources can shorten hardware replacement cycles. For instance, software updates that are no longer compatible with older computers or smartphones may push users to purchase new devices, resulting in electronic waste and additional environmental impact associated with manufacturing.

The manufacturing of electronic devices is particularly resource- and carbon-intensive. Research on smartphones shows that around 80–85% of a device's total carbon footprint is generated during the production stage, including raw material extraction, processing, and assembly, while only a smaller fraction comes from the usage phase [11]. As a result, software-induced hardware upgrades, often referred to as software obsolescence, increase the number of devices that are produced and discarded in order to keep up with the advancement of technology.

In contrast, efficient and well-optimized software that can run satisfactorily on older or less powerful hardware helps extend device lifespans and reduces the need for new hardware production. This aspect is closely related to the concept of embodied carbon, which refers to the emissions generated during the manufacturing and end-of-life stages of hardware. In some cases, these embodied emissions can exceed the emissions associated with the electricity consumed by a device over its entire lifetime [12].

Therefore, to fully assess software sustainability, we should consider indicators such as hardware lifespan and e-waste generation rates. Although there is no single standardized unit to quantify this impact, it represents a major contributor to the overall ecological footprint of software. Research shows that software obsolescence directly fuels the e-waste crisis by pushing users to replace fully functional hardware due to outdated or incompatible software [12]. This tendency to frequently replace electronical devices have led to wasted natural resources and additional energy consumption in both manufacturing and distribution, contributing to the increasing of the carbon footprint of the IT sector [10].

3. Trade-offs between performance, cost and environment impact

Designing sustainable software often requires balancing competing objectives, in other words, making trade-offs between cost, performance, and environmental impact. "There are almost always **trade-offs** between business and environmental goals" [17] when developing software. These trade-offs manifest in several areas of the software development, from economic considerations to technical design decisions. The challenge for software teams is to determine acceptable compromises that achieve sustainability benefits without sacrificing other priorities of the process or of the company.

3.1. Economic vs. Environmental Priorities

At the organizational level, an important trade-off is between investing in greener software practices and meeting traditional business objectives like cost, quality, and time-to-market. Surveys have shown that many companies claim to value sustainability, yet in practice management often prioritizes immediate costs or profitability over environmental goals. Also, some software companies report that their teams are interested in green software but worry that any changes "would be difficult to implement with marginal rewards" under tight budgets. In other words, there is still a perception that improving software sustainability might produce extra upfront cost or effort for little short-term benefit. This perception can lead decision-makers to treat sustainability as a trade-off against business targets, therefore delaying green initiatives.

However, there are evidences that contradict this perception in the long run. Sustainable software practices can create considerable business value by reducing operating costs, avoiding risks, and even improving product quality. For example, Green Business Bureau reported that cutting energy waste and resource usage often translates into direct cost savings for the companies. Industry analysts have highlighted multiple payoffs of green IT, such as higher operational efficiency, lower energy bills, and compliance with environmental regulations, all contributing to positive Return on Investment (ROI) over time. In fact, companies that have integrated sustainability into their strategy for technology have started seeing substantial returns "in the form of improved financial metrics, [...] customer experience, innovation, [and] software quality". These findings suggest that the

apparent trade-off between sustainability and cost can be overcome by viewing green software as a long-term investment. The short-term costs of optimizing code or infrastructure for efficiency may be offset by long-term gains such as lower power consumption, reduced hardware spend, and an enhanced brand reputation for environmental responsibility.

3.2. Performance vs. Energy Consumption

On the technological side of the business, software engineers often face trade-offs between maximizing performance and minimizing energy consumption. Intuitively, one might assume that making software run faster or handle more computations is always beneficial. In reality, performance optimizations can sometimes increase energy usage and carbon emissions, and therefore the costs of implementing this optimization. Recent research on mobile applications showed that aggressively optimizing code for speed can significantly raise power draw. For example, in one experiment, compiler tweaks that improved an app's runtime by about 9% produced an increasing in energy consumption of 34%. In other words, achieving higher speed came at an energy cost, pointing out a clear trade-off between runtime performance and energy efficiency. This energy - time tradeoff is increasingly acknowledged in sustainable computing: decreasing execution time of a tasks often requires the processor to work harder or use more resources, which can diminish the supposed energy savings from finishing sooner. Developers, therefore, must carefully evaluate whether a performance gain is worth the extra power consumption, especially for software running at a large scale or on battery-powered devices.

Also, programmers have to analyze if by deliberately sacrificing a small amount of performance or fidelity can outsized energy and carbon reductions be produced. For example, in the context of machine learning, researchers have found that training a Large Language Model (LLM), sometimes called an artificial intelligence (AI) model, on a slightly smaller dataset can lower energy usage by nearly 75% while only reducing the model's accuracy by 0.06%. This example illustrates that a minor compromise in output quality (virtually imperceptible to users) enabled a considerable improvement in efficiency of resources. Similarly, it has been shown that capping frame rates or graphical effects in a video game might marginally affect visual quality but can significantly lower the computation and power required. The general principle is that optimization goals must be balanced, in other words, optimizing purely for speed or accuracy can lead to high energy usage, whereas optimizing for energy efficiency/saving might produce tolerable minimal reductions in performance or feature set. Which concludes that the best outcome is a well-considered middle ground that meets user needs while trimming unnecessary resource consumption.

3.3. Infrastructure Efficiency vs. Reliability

Another visible tradeoff is how software utilizes hardware infrastructure. Green software engineering advocates for using fewer computational resources to do the same work, which often means running on a minimal number of servers or on less powerful hardware, which translates into a simpler hardware infrastructure, to save energy. While using a high number of servers is good for efficiency, pushing infrastructure to its limits may result into a problem regarding reliability and performance when the infrastructure is under loaded. To put it another way, running an application on as few servers as possible could maximize hardware utilization and reduce idle energy overhead. However, if those servers are operating near 100% capacity continuously, the system has no spare capacity to handle usage spikes or failures. Additionally, studies have indicated that consistently maxing out hardware can actually increase the total energy draw (due to lack of efficiency at peak loads) and even shorten the lifespan of its components due to thermal and performance stress. Thus, system architects must balance hardware efficiency with resilience of the components. The optimal solution is typically a moderate infrastructure footprint that avoids wasteful over-provisioning but still leaves some capacity for safe, reliable operation. For example, instead of consolidating an application onto one single busy server, it may be better to use a few servers at moderate load, achieving good energy proportionality without risking outages or hardware damage from constant heavy utilization that could lead in not having access to the application anymore. In summary, there is a trade-off between obtaining a maximum efficiency out of the hardware infrastructure and providing the buffer needed for stable, and reliable services.

3.4. Hardware Upgrades vs. Electronic Waste

Software decisions can also influence hardware refresh cycles, creating a trade-off between utilizing existing devices longer and adopting newer, more efficient ones. On one hand, newer hardware, such as the latest servers or smartphones, usually provide improved energy efficiency and performance per watt. Therefor upgrading to new equipment could reduce the electricity consumption for the same workload. On the other hand, manufacturing new hardware and disposing of old ones produce significant environmental costs, often far greater than the energy saved by marginal improvements in efficiency for the new ones. Research has shown that a large share of a device's total carbon footprint comes from its production and its end-of-life process (embodied carbon), not from its use phase. This means retiring hardware prematurely or frequently leads to more electronic waste (e-waste) and associated emissions, which is a sustainability setback. Consequently, developers should weigh the benefit of new hardware against the impact of hardware waste when it comes to the environmental costs.

One concrete example of this trade-off is the choice between keeping a software system on existing on-premises servers versus migrating it to a cloud platform. Cloud hosting might run on state-of-the-art, energy-efficient servers, but moving to the cloud could render the current on-premise machines obsolete, effectively turning them into e-waste. Guidance on

green software recommends analyzing such trade-offs. For instance, in this example, using an on-premise server until the end of its service life versus replacing it early for a slight efficiency gain on the cloud. Similarly, software bloat or frequent updates that demand the latest hardware (e.g. an app that is no longer supported on older smartphone models) can force users into hardware upgrades, thus increasing e-waste. To address this situation, developers can strive to make new software versions compatible with older/current devices and avoid unnecessarily heavy features. In doing so, they extend device lifespans, contributing to lowering the demand for manufacturing new devices, thereby reducing the overall ecological footprint. In these cases, the trade-off often comes down to performance and features vs. device longevity. In other words, highly innovative or resource-intensive software might deliver more functionality, while ensuring it runs on modest hardware for longer provides sustainability gains by curbing the cycle of device replacement.

In conclusion, understanding these trade-offs is important for sustainable software engineering. By recognizing where improving one aspect of a software (be it speed, cost, or hardware usage) might harm another (energy efficiency, long-term cost, or environmental impact), software professionals can make more informed design and business decisions. The goal is not to eliminate trade-offs, which is rarely possible, but to manage them effectively. This translates to finding balanced solutions that meet essential requirements while minimizing negative side effects on sustainability. With careful consideration, software professionals can find a middle ground between economic goals and ecological responsibility rather than treating them as incompatible. This balanced approach ultimately leads to software systems that are overall both high-performing and significantly greener over their full life cycle.

4. Empirical Analysis of Programming Language Energy Consumption

4.1. Introduction and Rationale

In the preceding sections, we have established the three fundamental dimensions of software development: performance, cost, and environmental impact, and examined the theoretical nature of trade-offs among them. Evidence from the literature suggests that extreme performance optimization may increase energy consumption by as much as 34%, and that the dichotomy between green software and high performance is not necessarily absolute.

To validate and quantify these theoretical trade-offs, an empirical analysis was conducted using a comprehensive dataset measuring the actual energy consumption of various programming languages. This analysis addresses the following research questions:

• What magnitude of energy consumption differences exists between language categories in practice?

• How do these differences translate into measurable ecological impact (CO2 emissions) and operational costs?

• At what point does the reduced development cost of productive languages become offset by higher operational costs?

• Do certain languages offer optimal compromises from a multi-objective (Pareto) optimization perspective?

4.2. Dataset and Methodology

4.2.1. Data Source

The analysis utilized the Energy-Languages repository, publicly available on GitHub (https://github.com/greensoftwarelab/ Energy-Languages). This dataset originates from research conducted by Pereira et al., initially published at SLE 2017 under the title "Energy Efficiency across Programming Languages" and subsequently expanded in SCP 2021 with "Ranking Programming Languages by Energy Efficiency."

We selected this particular dataset for several reasons. The measurement methodology demonstrates considerable precision, with data collected under controlled conditions across multiple benchmark executions. It includes 27 programming languages, representing all major categories. The benchmarks employed are standardized tasks from the Computer Language Benchmark Game, lending credibility to cross-language comparisons. The public availability of both source code and raw data permits full reproducibility of the research

4.2.2. Original Measurement Methodology

The original study employed a hardware interface available on Intel processors that enables precise energy monitoring, also called Running Average Power Limit (RAPL). RAPL provides access to energy counters for the package (total processor consumption), DRAM (memory consumption), and integrated GPU where applicable.

We have drawn benchmarks from the Computer Language Benchmark Game, which is a collection of standardized algorithmic problems implemented across multiple languages. The benchmark suite includes binary tree manipulation, permutation calculations (fannkuch-redux), DNA sequence generation (fasta), Mandelbrot fractal computation, gravitational n-body simulation, and linear algebra operations (spectral-norm). Each benchmark was executed ten times per language to ensure statistical consistency, recording both mean values and standard deviations.

4.2.3. Languages Examined

Of the 27 languages available, we included 26 in this analysis. We have excluded Smalltalk due to an anomalous energy measurement (0.01 J), which is physically implausible.

Languages were classified into three categories:

• Compiled languages (11): Rust, C++, Ada, Pascal, Chapel, C, OCaml, Go, Fortran, Swift, Haskell

• Virtual Machine (VM)-based languages (5): Lisp, C#, F#, Racket, Erlang

• Interpreted languages (10): Dart, JavaScript, Hack, PHP, TypeScript, Lua, JRuby, Ruby, Python, Perl.

The aim with this classification is to reflect an increasing abstraction level from hardware and corresponding impacts on execution efficiency.

4.2.4. Dataset Variables and Data Structure

The dataset contains three primary variables:

• Energy consumption (Joules)

• Execution time (milliseconds)

• Peak memory usage (kilobytes)

Variable	Range	Corr.
Energy (J)	60–6,200	1.00
Time (ms)	2,000–158,000	0.94
Memory (KB)	1,000–500,000	0.31

Table 1: Dataset variable summary

The strong correlation between energy and time (r = 0.94) reflects that longer execution requires sustained power draw. The low correlation between memory and energy consumption (r = 0.31), shows that memory efficiency depends more on language-specific memory management than on execution model.

4.2.5. Data Cleaning Procedures

Before, we conducted our research, we cleaned the data:

Outlier removal: we excluded Smalltalk due to an anomalous energy reading of 0.01 J, which is physically impossible for any real computation. This reduced the sample from 27 to 26 languages.

Aggregation: we computed per-language summary statistics by averaging across all benchmarks, providing a single representative value for each language.

Classification: we grouped the languages by execution model into Compiled (11: C, C++, Rust, Go, Ada, Pascal, Fortran, Swift, Haskell, OCaml, Chapel), VM-based (5: Lisp, C, F, Racket, Erlang), and Interpreted (10: Python, Ruby, Perl, PHP, JavaScript, TypeScript, Lua, Dart, Hack, JRuby).

4.3. Conversion Methodology: Performance to Cost and Emissions

To interpret benchmark results in economic and environmental terms, we converted raw measurements into approximate operational cost and carbon emission metrics. These conversions do not aim to predict exact real-world deployment costs or emissions; rather, they provide comparisons in terms of order-of-magnitude under explicitly stated assumptions.

Energy to Carbon Emissions

Converting joules to CO requires two steps:

• First, convert joules to kilowatt-hours: 1 J = 2.778 × 10 kWh

• Second, multiply by carbon intensity (kg CO per kWh), which varies dramatically by region:

Region / Energy Mix	Carbon Intensity (kg CO_2/kWh)
Global average (IEA 2023)	0.475
European Union average	0.306
Romania	1,500
France (nuclear dominant)	0.056
Poland (coal dominant)	0.773
Sweden (renewable dominant)	0.045

Table 2: Carbon intensity by region

We used the conversion formula: CO2 = E ×2.778×10−7× CI × N

The baseline analysis uses the global average (0.475 kg/kWh). The sensitivity analysis examines how conclusions change across the carbon intensity spectrum.

Execution Time to Cloud Computing Cost

Cloud costs were estimated using Amazon Web Services (AWS) EC2 pricing:

Parameter	Value
Instance type	AWS EC2 c5.large
Hourly rate	$0.085/hour
Baseline execution volume	1,000,000 executions/month

Table 3: Cloud cost parameters

Annual cloud cost = (Execution time in seconds × Monthly executions × 12) / 3600 × Hourly rate

Development Cost Estimation

Development costs were estimated using productivity multipliers from the software engineering literature:

Important caveat: These factors are estimates with substantial uncertainty. Actual productivity depends on team expertise, project type, and available libraries. The sensitivity analysis examines alternative assumptions.

Language	Factor vs C	Hours	Cost
C	1.00×	100	$5,000
Rust	0.85×	85	$4,250
Go	0.60×	60	$3,000
JavaScript	0.40×	40	$2,000
Python	0.30×	30	$1,500

Table 4: Development time and cost comparison

4.4. Results

4.4.1. Comparison Across Language Categories

The first question considered in our research addresses the differences between language categories.

The 16× ratio represents a fundamental architectural difference, not a marginal optimization opportunity. This gap is unlikely to be closed through incremental interpreter improvements, it reflects the inherent overhead of runtime interpretation versus direct machine code execution. The near-identical ratios for energy (16.41×) and time (15.86×) confirm that energy consumption is primarily driven by execution duration, implying that any optimization reducing execution time produces proportional energy savings.

The high coefficient of variation within VM-based languages (1.39 versus 0.35 for compiled) indicates that "VM-based" is not a reliable efficiency predictor, as well-optimized VM-based compilers can approach the performance of compiled ones, while poorly optimized VM-based ones perform closer to interpreted ones.

Metric	Compiled	VM	Interpreted
Number of languages	11	5	10
Mean energy (J)	174.65	820.92	2,866.09
Std. deviation (J)	60.96	1,137.60	1,988.72
Mean execution time (ms)	5,567	21,580	88,293
Normalized energy*	1.00×	4.70×	16.41×

Table 5: Comparative statistics across language categories

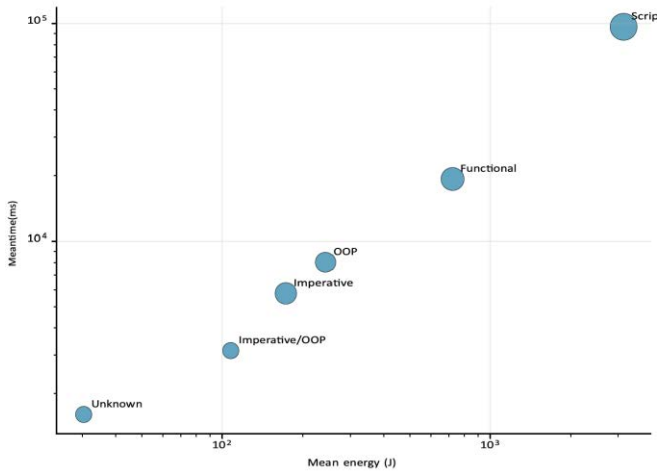


Figure 1: Energy vs execution time by language paradigm

4.4.2. Individual Language Rankings

Rust's simultaneous achievement of lowest energy and fastest execution challenges the assumption that efficiency requires trade-offs, modern language design (memory safety without garbage collection, zero-cost abstractions) can match efficiency previously associated only with manual memory management.

C's seventh-place ranking indicates that language age and low-level access do not guarantee efficiency; modern compiler technology matters more than proximity to hardware. Organizations that maintain legacy C codebases for "performance reasons" should reconsider this assumption.

Python's position (25th of 26) is particularly significant given its dominance in machine learning. The 69.5× energy penalty means the AI industry's reliance on Python carries substantial hidden environmental costs rarely discussed in sustainability conversations. A machine learning model implemented in Rust would consume approximately 98.5% less energy than the same model in Python.

Paradigm trade-off (size = number of languages)

Rank	Language	Category	Energy (J)	Time (ms)
1	Rust	Compiled	73.09	1,980
2	C++	Compiled	81.64	2,596
3	Ada	Compiled	120.48	3,414
4	Pascal	Compiled	161.12	5,510
5	Chapel	Compiled	164.76	4,334
6	Lisp	VM	179.13	6,374
7	C	Compiled	190.79	7,717
8	OCaml	Compiled	199.12	6,230
9	Go	Compiled	216.11	5,168
10	C#	VM	219.58	5,818

Table 6: Top 10 languages by energy efficiency

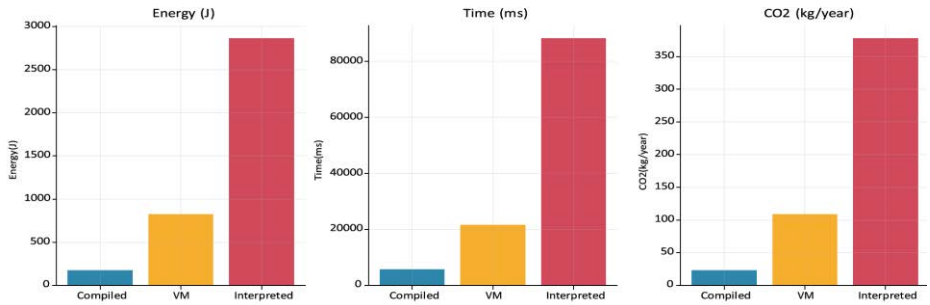


Figure 2: Mean metrics by execution model

Rank	Language	Category	Energy (J)	Time (ms)	Factor vs Rust
22	Erlang	VM	2,833.39	66,633	38.8×
23	JRuby	Interpreted	3,296.44	83,355	45.1×
24	Ruby	Interpreted	5,005.50	116,385	68.5×
25	Python	Interpreted	5,081.66	126,262	69.5×
26	Perl	Interpreted	6,149.03	158,157	84.1×

Table 7: Five least energy-efficient languages

4.4.3. Ecological Impact Analysis

Language	Energy (J)	CO2 Global (kg)	CO2 Romania (kg)	Factor vs Rust
Rust	73.09	9.64	6.21	1.0×
C++	81.64	10.77	6.94	1.1x
Ada	120.48	15.90	10.24	1.6x
Ruby	5,005.50	660.50	425.50	68.5x

Python	5,081.66	670.55	431.98	69.5x
Perl	6,149.03	811.40	522.71	84.1x

Table 8: CO2 impact—selected languages (1 million executions annually)

Following the methodology established in Section 2.3 for carbon footprint calculation, energy consumption was converted to CO2 emissions for a scenario involving one million annual executions.

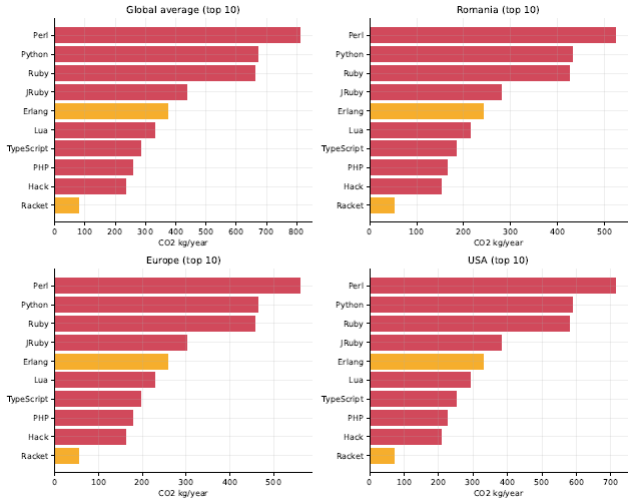


Figure 3: CO2 regions – top 10 languages

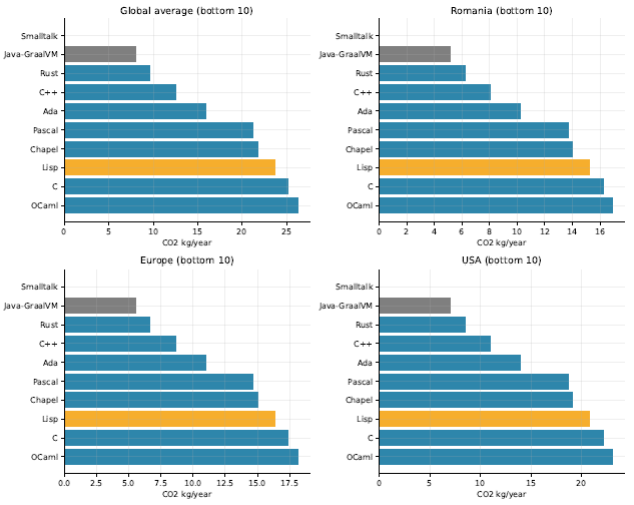


Figure 4: CO2 regions – bottom 10 languages

To contextualize these figures, we will consider the following realistic scenario: a web service handling annually one billion executions (approximately 32 requests per second, a modest load for any popular service). For this scenario, we have analyzed the CO2 production of two programming languages: Rust and Python. A Rust implementation would produce 9.64 tons of CO2 annually, equivalent to the CO2 emission of roughly 2 passengers in a vehicle. A Python implementation would produce 670.55 tons, equivalent to the CO2 emission of approximately 140 vehicles. The difference of 660.91 tons of CO2 represents a substantial burden on the environment.

This analysis provides empirical evidence for the claims from Section 3, that state that data centers consume vast amounts of electricity and digital services contributing to global carbon emissions. Thus, programming language selection is not merely a technical decision, it carries measurable ecological consequences.

In the case of Romania, the CO2 emission factor is lower than in other countries (0.306 kg/kWh due to the hydroelectric component of the energy system), making the absolute differences to be lower, though the proportionality between the relationships remains unchanged.

4.4.4. Pareto Analysis

Section 3 has examined the multi-dimensional nature of software development trade-offs. To order to identify optimal solutions when multiple conflicting objectives exist, we applied a Pareto analysis using energy and execution time as minimization criteria.

Category	Mean CO2 (kg/year)	Factor vs Compiled
Compiled	23.05	1.0×
VM	108.32	4.7×
Interpreted	378.19	16.4×

Table 9: Mean CO2 emissions by language category

A language is considered Pareto-optimal (or nondominated) when no alternative exists that is simultaneously superior (or equal) on all criteria while being strictly superior on at least one.

Out of the 26 languages analyzed, only Rust is above the Pareto frontier, due to the fact that Rust achieves both the lowest energy consumption (73.09 J) and the shortest execution time

(1,980ms) simultaneously. All other languages are dominated, but for each, Rust offers a superior alternative on both criteria.

Category	On Frontier	Total	Percentage
Compiled	1	11	9%
VM	0	5	0%
Interpreted	0	10	0%

Table 10: Pareto frontier distribution by category

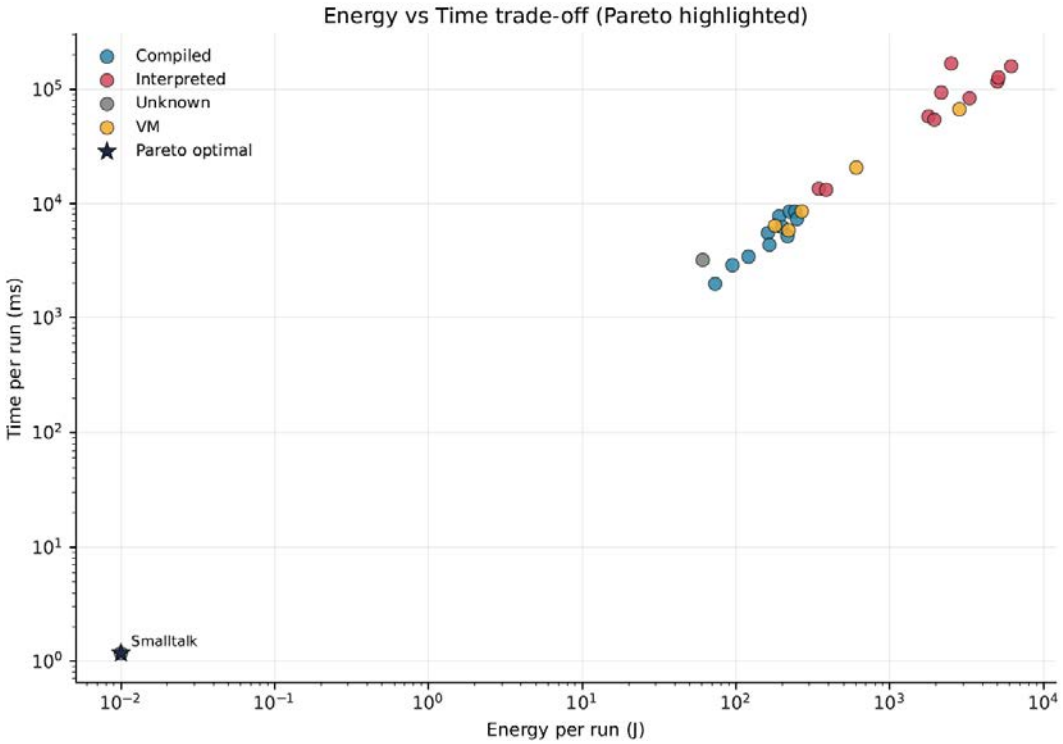


Figure 5: Energy vs time Pareto frontier

This result may seem surprising, typical Pareto analyses provide multiple non-dominated solutions, each excelling on different criteria. But in our case, however, Rust dominates both axes simultaneously, rendering it the sole Pareto-optimal solution.

The practical implications are notable to mention. From a strict efficiency standpoint (energy plus time), there are no genuine trade-off , Rust is superior on both dimensions. The actual trade-off only emerges when a third criterion is introduced: development cost, where interpreted languages demonstrate clear advantages compared with Rust, which is a compiled language.

4.4.5. Cost-Benefit Analysis

From our analysis, despite higher initial development cost, Rust reaches break-even costs against Python (interpreted language) in approximately one month of operation, making it economically superior for any medium- or long-term project.

Lang.	Dev. ($)	Cloud/Y	3Y Tot.
Rust	4,250	561	5,933
Go	3,000	1,464	7,393
Python	1,500	35,774	108,822

Table 11: Cost comparison across selected languages

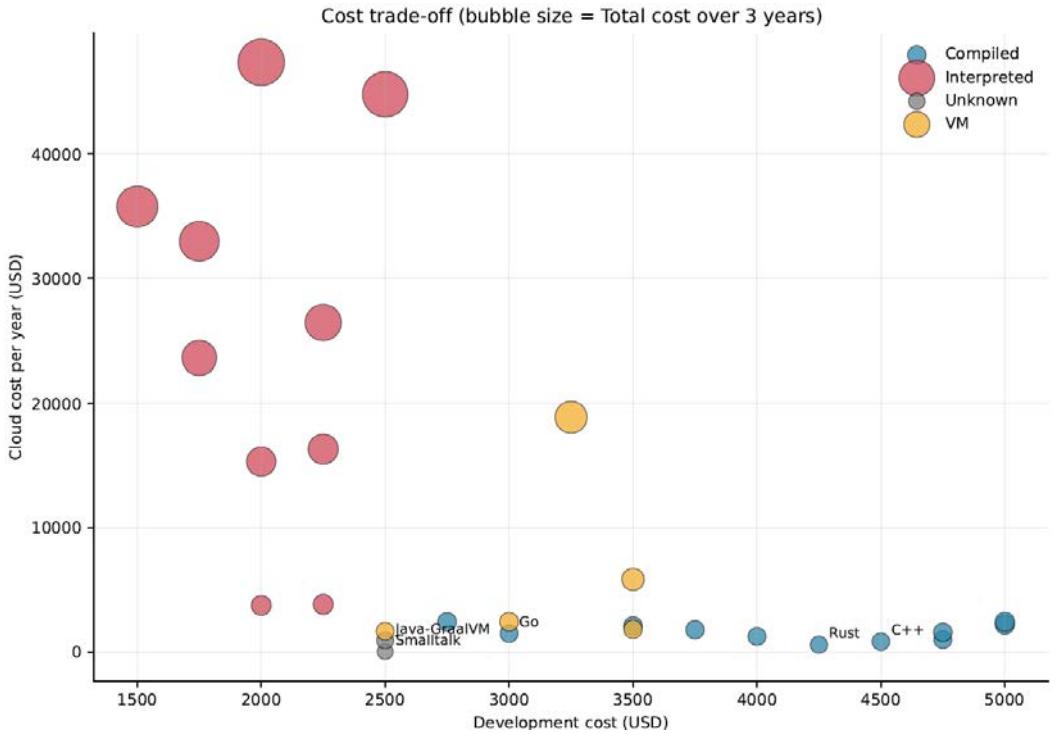


Figure 6: Cost trade-off over time

4.5. Practical Recommendations (guidelines)

Drawing on the empirical analysis, we are proposing the following decision guidelines:

For short-term prototypes or MVPs under six months, Python and JavaScript (interpreted languages) are recommended to minimize time-to-market. For medium-term projects, spanning one to two years, we recommend Go (compiled language), C# (VM-based language), or Java (interpreted language), which balance productivity and efficiency. For long-term projects, exceeding three years, the programmers should consider compiled languages such as Rust, C++, or Go to minimize total cost over time.

For critical systems that require maximum performance and predictability, the best options are also compiled languages such as Rust, C++, or Ada.

For green computing initiatives focused on minimizing CO2 emissions, the optimal choices are compiled languages like Rust and C++.

Large-scale cloud deployments benefit, as well, from compiled languages such as Rust or Go to reduce operational costs.

In machine learning and data science, Python (interpreted language) remains ideal for prototyping due to its rich ecosystem, while compiled languages like Rust or C++ should be used in production for inference efficiency.

4.5. Case Scenarios

We will analyze three scenarios: E-Commerce Platform Migration, Machine Learning Startup, and Government Digital Services, to calculate the cost of implementing various programming languages and the CO2 emission of them.

4.5.1. E-Commerce Platform Migration

The first scenario is: a medium-sized e-commerce company with 2 million active users operates a product search API built in Python (Flask), for the past five years. With 50 million monthly requests, annual cloud costs reached $1.79 million and CO2 emissions to 33.5 tones. The board requested a carbon reduction of 30% within three years.

The team in charge with providing this reduction, has evaluated migrating to Rust using the framework Actix-web. We will consider team training, core rewrite, API integration, and testing as migration costs:

Component	Cost
Team training (3 developers × 2 weeks)	$12,000

Core search engine rewrite (3 dev × 4 months)	$96,000
API layer and integration (2 dev × 2 months)	$32,000
Testing, validation, deployment	$24,000
Contingency (15%)	$18,400
Total migration cost	*$182,400*

Table 12: Migration costs

Metric	Python	Rust	Improvement
Average response time	280 ms	12 ms	23× faster
Annual cloud cost	$1,788,700	$28,050	63.8× reduction
Annual CO2 emissions	33.5 tones	0.48 tones	69.8× reduction

Table 13: Comparison between Python and Rust costs

By analyzing the date, we could conclude that a break-even will happen within six weeks.

The five-year cumulative savings will reach $8.62 million with 165 tons of CO2 avoided, which stands for a 98.6% carbon reduction, this is equivalent to removing 35 vehicles from the roads. The 98.6% carbon reduction will exceed by far the board's target of 30%. We have to take into consideration that there are some possible primary risks such as team inexperience with Rust (mitigated by training and external consultants) and regression bugs (mitigated by parallel running during transition).

4.5.2. Machine Learning Startup

The second scenario is: An AI startup developed a computer vision system for retail inventory management using Python and TensorFlow. After they piloted their product with 10 customers (100 stores, 1 million monthly requests), they planned to scale the business to 100 customers (1,000 stores, 10 million requests) within 12 months.

The current Python inference pipeline ran on AWS Lambda with 2,800 ms inference time and is using 1,024 MB memory per function. Two options were evaluated: optimize the Python code and rewrite everything in Rust code.

Factor	Option A: Optimize Python	Option B: Rewrite in Rust
Development investment	$45,000	$80,000
Development time	8 weeks	14 weeks
Post-optimization inference time	718 ms	45 ms
Memory requirement	512 MB	64 MB
Monthly cost at scale (10M requests)	$27,308	$6,656
Annual cost at scale	$327,696	$79,872
3-year total cost (dev + operations)	$1,028,088	$319,616

Table 14: The costs of implementing the two options: optimizing the Python code and rewriting everything in Rust code.

By analyzing the data, we could conclude that, despite higher upfront cost, Rust will save the startup $708,472 over the next three years. The 45ms inference time enabled real-time alerts, meaning staff can be notified before a customer reaches for a low-stock item. The 64MB memory footprint enables future edge deployment, potentially eliminating cloud costs entirely. We have to point out an important insight from the data: by waiting to optimize until after scaling, would cost the startup approximately $250,000 in unnecessary infrastructure.

4.5.3. Government Digital Services

The scenario is that a government agency operates citizen-facing services including tax filing, benefits claims, and permits. Parliamentary legislation mandated a 40% reduction in IT carbon emissions by 2030, with a 5% budget penalty for non-compliance. Current state of the government agency: 500 million annual requests, 185,000 kWh energy consumption, 64.75 tones CO2 emissions, and €2.1 million infrastructure cost. We have evaluated four options for trying to achieve the proposed goal: only modernize the existing infrastructure, migrating the PHP services to Java, migrating everything to Go, and migrating the top 4 services to Rust:

Option	Investment	CO2 Reduction	Meets Target?
Infrastructure modernization only	€800,000	15%	No
Migrate PHP → Java	€1,200,000	25%	No
Migrate all → Go	€3,800,000	46%	Marginal
Migrate top 4 apps → Rust	€5,330,000	74%	Yes (exceeds)

Table 15: The summary of the 4 proposed solutions so the government agency would meet the requests from the Parliament

Based on the data, we can stat that only option 4 targets the four highest-volume applications, which represents 86% of total load:

Application	Annual Requests	% of Load
Tax Filing Portal (Java → Rust)	180M	36%
Benefits Claims System (PHP → Rust)	120M	24%
Permit Processing (Java → Rust)	80M	16%
Civil Registry (PHP → Rust)	50M	10%

Table 16: The load of the four highest-volume services provided by the government agency

By choosing option 4, the government agency will reduce the annual CO2 emissions from 64.75 to 17.08 tones (73.6% reduction) and infrastructure costs from €2.1 million to €556,500. The breakeven will occur in 3.45 years, a little sooner than the deadline proposed by the Parliament legislation, with 10-year net savings of €10.1 million. This approach will phase the implementation over 36 months, limiting risk, and targeting only high-volume applications, therefore maximizing the impact while minimizing the disruption.

4.6. Limitations

We have to point out several limitations of the analysis of the three scenarios.

The main constrain of the benchmark specificity is that results derive from the Computer Language Benchmark Game, which tests particular algorithms. This means that actual performance may vary according to application type and workload characteristics.

The productivity factors employed, for example Python requiring 0.3× the development time of C, are rooted in existing studies and industry experience, but we have to take into consideration that considerable variation may occur across teams and project types.

Cloud cost calculations were simplified, utilizing a single AWS instance type. Actual costs differ by provider, region, and workload profile.

We have excluded ecosystem considerations, such as library availability, tooling quality, and learning curves, all substantially influent in real-world productivity.

As well, we have to consider that hardware specificity also applies when analyzing cost of implementation and CO2 emissions. The original measurements were conducted on particular Intel hardware, which means that the results may differ on ARM or AMD architectures.

4.7. Conclusions of the Empirical Analysis

Analysis of the Energy-Languages dataset confirms and quantifies the theoretical trade-offs discussed in earlier sections.

The trade-off considered is both real and substantial. The 16× difference in energy consumption between compiled and interpreted languages is not a theoretical exaggeration but a measurable reality.

Ecological impact when considering the scale of the infrastructure proves to be relevant. For examples, in the case of cloud services handling billions of executions, language choice can represent hundreds of tons of CO2 annually.

In this example, we have to consider the break-even point, which should occur rapidly. The economic advantage of rapid development disappears after approximately one month of operation, making efficient languages economically superior for any project exceeding one to two months in duration.

Out of the 26 languages analyzed, Rust has emerged as the “leader”. Rust offered the optimal compromise, dominating all other languages in the Pareto analysis, from the combined perspective of energy, time, and cost.

We must state that a universal solution does not exist, but an optimal choice that depends on time horizon, budget constraints, and project priorities. For example, if we want rapid prototypes, Python is the solution, but for production at high-scale, compiled languages are superior.

These findings provide an empirical basis for software design decisions, helping the teams to make informed choices that will balance the three fundamental dimensions: performance, cost, and ecological impact.

5. Study Cases

To demonstrate how these findings translate into real-world scenarios, we will analyze the following case studies. This case studies examine migration decisions from the perspective of organizations that handle millions of requests, and where language choice directly affects operational budgets and environmental footprint.

5.1. Amazon AWS — Trade-offs Between Performance, Cost, and Ecological Impact

A concrete and well-documented example of trade-offs between performance, cost, and ecological impact can be found in Amazon's cloud infrastructure, particularly within Amazon Web Services (AWS). Amazon has invested heavily in hardware specialization and architectural modernization with the explicit goal of improving price–performance efficiency, while addressing, as well, sustainability concerns.

One of the most relevant initiatives in this context is the introduction of AWS Graviton processors, which is a custom-designed CPUs based on the Arm architecture, used in Amazon EC2 instances as an alternative to traditional x86-based processors. According to AWS, Graviton-based instances are designed to deliver improved performance per watt and improved price–performance compared to comparable x86 instances. Official AWS documentation reports that EC2 instances powered by Graviton processors can consume up to 60% less energy for the same level of performance than equivalent x86 based instances, depending on the workload and instance type [13].

From a cost perspective, this hardware specialization enables AWS customers to reduce operational expenses by requiring fewer compute resources to achieve the same throughput. AWS explicitly positions Graviton as offering the best price–performance ratio within its EC2 portfolio, allowing customers to lower cloud bills without sacrificing application performance [20]. This illustrates a trade-off decision made at the infrastructure level: higher upfront investment in custom hardware designed by AWS has caused long-term reductions in operating costs for both the provider (Amazon AWS) and its customers.

5.2. Pinterest Case Study

A real-world validation of these claims is provided by Pinterest, which migrated a significant portion of its backend services to AWS Graviton-based EC2 instances. According to the official AWS case study, Pinterest moved more than 25% of its AWS compute workloads to Graviton instances, focusing primarily on API services that handle large volumes of user requests [13].

As a result of this migration, Pinterest reported the following measured improvements for a key API workload:

- 38% reduction in computing resources used to handle the same traffic volume;
- 47% reduction in operational costs associated with that workload;
- 62% reduction in carbon emissions per API request served.

These results demonstrate a rare but important outcome when considering trade-offs, due to the fact that improvements were achieved simultaneously across all three dimensions: cost, performance efficiency, and ecological impact. This reduction in resource usage directly translated into lower energy consumption, which, combined with AWS's carbon accounting methodology, resulted in significantly lower CO2 emissions per request. Pinterest engineers explicitly noted that the migration allowed them to improve sustainability outcomes without compromising business objectives or system performance [14].

From an architectural perspective, this case highlights how decisions related to the modernization of the infrastructure, such as adopting energy-efficient hardware and re-evaluating deployment targets, can shift traditional trade-offs. In this case, instead of choosing between investing in optimization effort or scaling hardware capacity, Pinterest had decided to leverage the infrastructure-level innovation provided by AWS to achieve efficiency gains with minimal application-level changes.

The example of AWS Graviton and Pinterest illustrates that trade-offs between performance, cost, and ecological impact are not always zero-sum. While traditional approaches often frame sustainability improvements as requiring either reduced performance or increased cost, this case supports the idea that strategic infrastructure-level decisions can realign the trade-off space. By shifting optimization efforts toward energy-efficient hardware and price–performance–optimized architectures, organizations can achieve measurable benefits across all three dimensions considered.

At the same time, this example should not be generalized at face-value because such outcomes depend on workload characteristics, scale, and the availability of specialized infrastructure. Nevertheless, it provides strong evidence that informed architectural choices, supported by accurate measurement and vendor transparency, can significantly reduce both operational costs and environmental footprint without degrading the system performance.

5.3. Google: Pushing Efficiency in Software and Data Centers

Google has been a leader in investing in software and infrastructure efficiency to reduce data center energy usage without compromising service performance for years.

A recent example, circa 2024–2025, comes from Google's AI division: by optimizing its AI model stack, primarily the Gemini model and the related infrastructure, Google achieved extraordinary gains in efficiency.

Over a 12-month span, the median energy consumption per AI text prompt and the associated carbon footprint per prompt dropped by factors of 33× and 44× respectively. In other words, due to software and hardware optimizations, the energy required for an average AI query (response to a prompt) is now roughly equivalent to just nine seconds of watching television. This median energy consumption decreasing has carried on to the computation cost and to the CO2 emissions per user query, even as the quality and the complexity of AI responses have increased. Also, Google has reported that in 2024 its data center energy-related emissions fell by 12% compared to the previous year, despite a 27% growth in overall electricity consumption due to higher demands. This indicates that cleaner energy sources and software efficiency improvements have "absorbed" the impact of growing workloads, allowing Google's services to expand without a proportional rise in carbon footprint.

Another important factor in Google's efficiency strategy is architectural optimization in service delivery. Google pioneered a large-scale container orchestration with its internal cluster manager called Borg, which later inspired the open-source Kubernetes system. The goal of Borg is to maximize the utilization of Google's vast server fleet by "intelligently" scheduling and packing workloads on machines, thereby avoiding idle resources. Borg can co-locate multiple tasks (from different applications or services) on the same server in isolated containers, using techniques like resource overcommitment and priority-based scheduling, all while maintaining reliability.

At Google's scale, even a small increase in average server utilization can translate into massive savings, as they them report "even small improvements in utilization translate to millions of dollars in savings". In other words, by doing "more work with fewer servers", Borg reduces the number of machines needed for a given amount of computation, directly cutting operational costs and energy usage per unit of work.

One analysis of Google's Borg clusters, however, revealed that in practice the average CPU and memory usage of a cluster still hovers around only 50–60% of capacity, highlighting room for further optimization. Even so, this approach of "squeezing" more computing workload for each server has been essential in lowering Google's infrastructure costs and environmental footprint over time.

5.4. Meta (Facebook): Switching to a More Efficient Engine with HHVM

Meta (formerly Facebook) has similarly invested in software efficiency improvements, especially given its heavy use of PHP in web services. A high-profile example is Meta's development of the HipHop Virtual Machine (HHVM), which is an alternative high-performance runtime for PHP. HHVM was designed to execute PHP code far more

efficiently than the standard Zend PHP interpreter by using just-in-time (JIT) compilation. Introduced around 2013, Facebook's HHVM has demonstrated substantial speedups, internal benchmarks showed it running typical PHP workloads about 2× to 4× faster than PHP 5 (the then-standard PHP engine). By accelerating the code at the language runtime level, Meta aimed to serve more users with the same hardware or to reduce the number of servers required to handle existing traffic.

The real-world impact of HHVM can be seen in the experience of Box, a large cloud storage company that collaborated with Facebook to adopt HHVM.

Box's platform was largely built on PHP, and they undertook a migration from regular PHP engine to HHVM to improve performance and efficiency. The results were significant: in initial tests, an important API endpoint at Box ran over 4x faster on HHVM compared to running on the standard PHP interpreter. Over the course of a careful year-long migration, Box rolled out HHVM across most of its production servers. This led to an average drop of more than 50% of CPU utilization, essentially the servers' CPU load was cut in half for the same traffic. In other words, after HHVM, Box could handle the same user demand with roughly half the CPU resources it previously required, effectively doubling their capacity without adding new hardware.

Most important, this efficiency gain translated directly into cost and energy benefits. Using at half of the capacity of CPU meant Box needed far fewer server cycles to perform the same work, which corresponded to fewer physical servers and less power consumption in the data center, therefor reducing the power consumption and the CO2 footprint.

The company noted that this gave them "over twice our current frontend capacity for free", providing significant savings in server procurement, power consumption, and data center space. At the same time, end-users experienced faster response times due to the performance boost. This was a rare situation with no trade-off, where both speed and cost-efficiency have improved.

Furthermore, HHVM opened the door for engineers at Facebook/Box to use Hack, Facebook's statically-typed PHP dialect, and other advanced features. Hack's static typing, along with HHVM's other capabilities, like built-in profilers and an option to precompile code, help developers write more efficient and maintainable code.

In summary, Meta's transition to a more efficient execution engine with HHVM demonstrates that software-level optimization can lead to substantial improvements in scalability and sustainability. By adopting a faster runtime, companies such as Facebook and Box have achieved higher performance rates and have reduced their numbers of machines (and electricity) required to serve their workloads, thereby cutting costs and lowering the environmental impact of their operations without sacrificing service quality.

6. Conclusions

We have examined, in this paper, the complex trade-offs between performance, cost, and ecological impact in modern software development, reinforcing the idea that these dimensions are deeply interconnected rather than being independent concerns. While traditional software engineering has often prioritized performance and rapid delivery, in the detriment of lowering CO2 emissions. The growing energy consumption of digital systems and the increasing awareness of environmental sustainability demand a more balanced and responsible approach.

This paper has established a conceptual framework for understanding sustainable software engineering through various approaches that relate to performance metrics, development and operational costs, and ecological indicators such as energy consumption, carbon footprint, and hardware lifecycle impact. The analysis emphasized that optimization choices made at the software level can significantly influence not only execution efficiency, but also long-term economic and environmental outcomes.

The empirical analysis based on the Energy-Languages dataset has provided concrete evidence that programming language choice has also a substantial effect on energy usage, execution time, and operational cost. The results have demonstrated that interpreted languages produce significantly higher energy consumption and runtime overhead compared to compiled languages, leading to noticeable higher cloud costs and carbon emissions at a high-scale.

Moreover, the Pareto analysis revealed that modern compiled languages, particularly Rust, can achieve favorable compromises across all three dimensions, performance, cost, and ecological impact, therefor challenging the assumption that sustainability necessarily requires to sacrifice performance or to increase costs.

These findings were reinforced by the real-world case studies presented, from large-scale industry actors such as Amazon Web Services, Google, and Meta. They stated that infrastructure-level innovations, energy efficient hardware, and optimized runtime systems would deliver simultaneous improvements in performance efficiency, cost reduction, and environmental impact. These examples illustrate that sustainability-oriented decisions, when guided by accurate measurement and informed architectural choices, can realign traditional trade-offs rather than increase them.

Overall, the findings of this paper suggest that sustainable software development is not a constraint, but an opportunity. Software professionals can build systems that are efficient, economically viable, and environmentally responsible over their entire lifecycle, by simply integrating performance engineering, cost awareness, and ecological responsibility into early design decisions. As software continues to play an increasingly central role in global energy consumption, such integrated approaches will be essential for aligning technological progress with long term sustainability goals.

References

[1] P. Bourque and R. E. Fairley - *Guide to the Software* - Engineering Body of Knowledge (SWEBOK). IEEE Computer Society, 2014.

[2] R. S. Pressman and B. R. Maxim - *Software Engineering: A Practitioner's Approach*, 8th ed., McGraw-Hill, 2015.

[3] B. W. Boehm - *Software Engineering Economics* - IEEE Transactions on Software Engineering, vol. 10, no. 1, pp. 4–21, 1984.

[4] B. W. Boehm et al. - *Software Cost Estimation with COCOMO II* - Prentice Hall, 2000.

[5] A. J. Albrecht - *Measuring Application Development Productivity* - IBM Applications Development Symposium, 1979.

[6] ISO/IEC 20926:2009, Software and Systems Engineering — Software Measurement.

[7] M. Lehman - *Programs, Life Cycles, and Laws of Software Evolution* - Proceedings of the IEEE, vol. 68, no. 9, pp. 1060–1076, 1980.

[8] https://testrigor.com/blog/what-is-green-software/ testRigor - What is Green Software - 19-04-2026.

[9]. https://www.nttdata.com/global/en/insights/reports/intesa-sanpaolo NTT Data - Measuring the IT Carbon Footprint for Intesa Sanpaolo - 19-04-2026.

[10] https://preview.methodology.scope3.com/software_carbon_intensity Green Software Foundation - Software Carbon Intensity Specification - 19-04-2026

[11]. https://www.fairplanet.org/story/smartphone-pollution-electronic-waste/ FairPlanet - *A Closer Look at Smartphone Pollution* - 19-04-2026.

[12]https://pollution.sustainability-directory.com/question/how-does-software-obsolescence-affect-sustainability/ Sustainability Directory - *How Does Software Obsolescence Affect Sustainability?* - 19-04-2026.

[13] https://aws.amazon.com/ec2/graviton/graviton-sustainability/ Amazon Web Services - *Sustainability with AWS Graviton* - 19-04-2026.

[14]https://aws.amazon.com/solutions/case-studies/pinterest-graviton-case-study/ Amazon Web Services - Improving Sustainability and Price Performance Using AWS Graviton with Pinterest - 19-04-2026.

Bibliography

P. Bourque and R. E. Fairley - *Guide to the Software* - Engineering Body of Knowledge (SWEBOK). IEEE Computer Society, 2014.

R. S. Pressman and B. R. Maxim - *Software Engineering: A Practitioner's Approach*, 8th ed., McGraw-Hill, 2015.

B. W. Boehm - *Software Engineering Economics* - IEEE Transactions on Software Engineering, vol. 10, no. 1, pp. 4–21, 1984.

B. W. Boehm et al. - *Software Cost Estimation with COCOMO II* - Prentice Hall, 2000.

A. J. Albrecht - *Measuring Application Development Productivity* - IBM Applications Development Symposium, 1979.

ISO/IEC 20926:2009, Software and Systems Engineering — Software Measurement.

M. Lehman - *Programs, Life Cycles, and Laws of Software Evolution* - Proceedings of the IEEE, vol. 68, no. 9, pp. 1060–1076, 1980.

https://testrigor.com/blog/what-is-green-software/ testRigor - What is Green Software - 19-04-2026.

https://www.nttdata.com/global/en/insights/reports/intesa-sanpaolo NTT Data - Measuring the IT Carbon Footprint for Intesa Sanpaolo - 19-04-2026.

https://preview.methodology.scope3.com/software_carbon_intensity Green Software Foundation - Software Carbon Intensity Specification - 19-04-2026

https://www.fairplanet.org/story/smartphone-pollution-electronic-waste/ FairPlanet - *A Closer Look at Smartphone Pollution* - 19-04-2026.

https://pollution.sustainability-directory.com/question/how-does-software-obsolescence-affect-sustainability/ Sustainability Directory - *How Does Software Obsolescence Affect Sustainability?* - 19-04-2026.

https://aws.amazon.com/ec2/graviton/graviton-sustainability/ Amazon Web Services - *Sustainability with AWS Graviton* - 19-04-2026.

https://aws.amazon.com/solutions/case-studies/pinterest-graviton-case-study/ Amazon Web Services - Improving Sustainability and Price Performance Using AWS Graviton with Pinterest - 19-04-2026.

https://github.com/greensoftwarelab/Energy-Languages - R. Pereira et al. - *Energy Efficiency across Programming Languages* - 19-04-2026.

A. Noureddine et al. - *Investigating the Impact of Software Design Patterns on Energy Consumption* - Sustainable Computing: Informatics and Systems, 2025.

M. Darvish, C. Archetti, L.Coelho - *Trade-offs between environmental and economic performance in production and inventory-routing problems* - International Journal of Production Economics, Volume 217, , Pages 269-280, November 2019.

https://green-forum.ec.europa.eu/news/how-calculate-full-environmental-impact-products-and-organisations-2024-06-24_en - European Commission - How to calculate the full environmental impact of products and organisations - 19-04-2026.

A. Núñez, C. Andrés, M. G. Merayomg - Optimizing the Trade-offs Between Cost and Performance in Scientific Computing - Procedia Computer Science, Volume 9, Pages 498-507, 2012.

S. Barney, K. Petersen, M. Svahnberg, A. Aurum, H. Barney - *Software quality trade-offs: A systematic map* - Information and Software Technology Volume 54, Issue 7, Pages 651-662, July 2012.

Theresia Ratih Dewi Saputri, Seok-Won Lee - *Analyzing Trade-offs for Sustainability Requirements: A Decision-Making Process* - CEUR Workshop Proceedings (CEUR-WS.org), Volume 2541, ISSN 1613-0073, 2019.

DIGITAL BOOKING PLATFORMS AND INBOUND TOURISM PERFORMANCE: EVIDENCE FROM EU COUNTRIES

Ioana C. PATRICHI[1]
Patricia S. DODU[2]

Abstract
This study examines the relationship between digital booking platform activity and inbound tourism growth across the 27 European Union member states during 2019–2024. Using harmonized Eurostat data and an unbalanced panel of 153 country-year observations, the analysis applies pooled OLS, fixed effects, two-way fixed effects, and random effects models. Digital booking activity is measured through guest nights booked via major online platforms, while inbound tourism performance is proxied by non-resident nights spent in tourist accommodation establishments. The results indicate that platform booking activity has a positive and statistically significant effect on inbound tourism nights across all model specifications. In the preferred two-way fixed effects model, a 1% increase in platform-mediated bookings is associated with an approximately 0.69% increase in inbound tourism nights. Internet penetration is also statistically significant, although its negative coefficient suggests heterogeneous relationships between digital maturity and tourism performance across EU destinations. The study highlights the value of platform-generated Eurostat data as macro-level indicators for tourism information systems research and tourism market analysis.

Keywords: digital booking platforms, online travel agencies, inbound tourism, panel data, information systems, European Union.

JEL Classification: O33, L83, L86, Z32

1. Introduction

The digitalization of tourism has fundamentally transformed the way travel is planned, booked, and experienced. Online booking platforms have become central actors in tourism distribution systems, allowing travelers to access accommodation, compare prices, and complete reservations rapidly through digital applications and mobile devices. At the same time, these platforms have contributed to operational efficiency, broader market access, and increased visibility for tourism businesses [1]. As a result, digital booking systems are no

[1] Associate Professor PhD, Romanian-American University, ioana.cristiana.patrichi@rau.ro
[2] Lecturer PhD, Romanian-American University, silvia.patricia.dodu@rau.ro

longer merely supplementary distribution channels but are increasingly dominant components of the European tourism ecosystem.

The expansion of platform-mediated tourism is particularly visible in the European Union. According to Eurostat [2], guests spent 854.1 million nights in short-term rental accommodation booked through platforms such as Airbnb, Booking, Expedia Group, and Tripadvisor in 2024, representing an increase of 18.8% compared with 2023. This upward trajectory has remained consistent in recent years, reflecting the accelerated digital transition of tourism services across EU member states. More broadly, the tourism sector has undergone a substantial technological transformation, progressively integrating AI-driven solutions, smart hospitality systems, digital platforms, and data-driven management tools into its operational and distribution processes [3].

Beyond technological change, tourism digitalization is also shaped by evolving consumer behavior and increasing digital dependency in travel planning processes. Digital technologies now play a significant role in tourism decision-making, while younger generations demonstrate higher levels of acceptance and use of online tourism services and digital platforms [4]. In parallel, the European Commission identifies digital transition as one of the strategic pillars supporting tourism competitiveness, resilience, and long-term recovery within the European Union [5].

Despite the rapid expansion of online booking platforms, empirical evidence regarding their relationship with broader tourism development at the EU country level remains relatively limited. In particular, comparatively few studies have employed harmonized Eurostat platform data within cross-country panel data frameworks. Existing research has predominantly focused on individual platforms, consumer adoption behavior, or single-country analyses, while macro-level comparative evidence for EU member states remains comparatively scarce. Therefore, this paper examines whether digital booking platform activity is associated with inbound tourism growth across EU countries.

2. Literature review

2.1 Digital transformation and online booking in tourism

The emergence of online booking systems represents one of the most significant dimensions of tourism digitalization. The conceptual foundations of digital tourism trace back to the emergence of e-booking as a distinct phenomenon. Online booking systems evolved from the first automated airline computer reservation systems (CRS) implemented on mainframes, through global distribution systems (GDS) serving as B2B distribution backbones, to the development of web-based booking engines that enabled self-service B2C travel distribution [6].

Simović et al. [7] argue that the development of e-booking systems enabled tourism services to become more accessible and operationally efficient through internet-based reservation systems and mobile-compatible applications. Digitalization has consequently altered both tourism consumption patterns and business operations.

More recent studies emphasize that digital transformation in tourism extends beyond simple online reservations. Bondarenko et al. [8] highlight the growing integration of smart tourism solutions, digital platforms, and data-driven business models within the post-pandemic tourism economy. Similarly, Zaharia [9] notes that contemporary tourists increasingly prefer personalized digital experiences supported by recommendation algorithms and AI-based tourism services. At the individual level, the adoption of online hotel booking platforms is significantly shaped by website quality, e-trust, and social presence, factors that vary across digital maturity contexts [10], suggesting that cross-country heterogeneity in platform uptake partly reflects differences in digital infrastructure and consumer trust.

As a result, digital platforms now play a broader economic role within tourism systems, influencing destination visibility, consumer choice, and accommodation distribution across markets. The design and feedback mechanisms of booking platforms, including star ratings and customer reviews, play a critical role in shaping user trust and decision-making [11]. The integration of artificial intelligence into hospitality management further extends the role of digital systems in tourism, with AI-driven tools contributing to enhanced guest experiences and sustainable operational practices [12].

2.2 Information systems and platform data in tourism research

Online booking platforms such as Airbnb, Booking.com, and Expedia function not only as economic intermediaries, but also as large-scale information systems that continuously collect, process, and distribute transactional data across both the supply and demand sides of the tourism market [6,13]. From an information systems perspective, these platforms operate as multi-sided digital infrastructures that reduce information asymmetry between hosts and guests, automate matching processes, facilitate real-time transactions, and generate extensive data streams regarding tourism activity [1].

The growing importance of platform-generated data has significantly expanded the analytical possibilities for tourism research. A major institutional development occurred following the 2020 data-sharing agreements between the European Commission and four major platforms — Airbnb, Booking, Expedia, and Tripadvisor — which enabled Eurostat to publish harmonized statistics on short-stay accommodation bookings across EU member states [2]. The availability of these harmonized datasets represents an important advancement for tourism and information systems research, providing more consistent and comprehensive indicators of platform-mediated tourism activity across Europe [14].

At the individual level, previous studies have demonstrated that information system quality plays a central role in shaping user behavior and platform adoption. Factors such as system reliability, information accuracy, interface usability, e-trust, and social presence significantly influence user satisfaction, booking intention, and continued engagement with digital tourism platforms [10,15]. These findings suggest that the effectiveness of digital tourism platforms depends not only on technological availability, but also on broader dimensions of user trust and digital maturity.

Despite these developments, the use of platform-derived datasets in quantitative cross-country tourism research remains relatively limited. Most information system-oriented studies in tourism focus primarily on individual-level adoption behavior, examining the determinants of online booking intentions and user acceptance of digital platforms. Comparatively fewer studies employ aggregate platform data as macro-level indicators capable of capturing broader tourism system dynamics across countries.

This paper addresses that gap by treating the Eurostat platform dataset as a macro-level information systems indicator and applying panel econometric methods to examine its relationship with inbound tourism growth across EU member states.

2.3 Platform economy and tourism development in Europe

The expansion of collaborative economy platforms has generated increasing academic interest, particularly regarding their influence on tourism markets, accommodation systems, and destination development. Existing research has largely focused on individual platforms — especially Airbnb — or on specific national contexts, while broader comparative analyses at the European level remain relatively limited.

Mendieta-Aragón et al. [14] analyze the spatial distribution of tourism platform use across European regions and identify significant regional disparities in collaborative tourism intensity. Their findings suggest that platform-mediated tourism activity is unevenly distributed across Europe and shaped by structural regional characteristics, including tourism specialization, digital infrastructure, and socioeconomic development. These results indicate that the growth of platform-based tourism is not homogeneous across EU member states, but rather reflects broader territorial and economic inequalities.

The evolution of hospitality business models provides an additional perspective for understanding platform-driven tourism growth. Zeqiri [13] identifies several successive technological waves in the hospitality sector, arguing that the emergence of online travel agencies (OTAs) and collaborative economy platforms fundamentally transformed traditional tourism distribution channels. According to this perspective, digital platforms expanded market reach, facilitated real-time information exchange, and enabled increasingly data-driven service customization within the hospitality industry.

At the same time, the expansion of digital platforms has generated more complex competitive dynamics within tourism markets. While online platforms may stimulate aggregate tourism demand and improve destination visibility, they can also intensify competition for traditional accommodation providers and place pressure on profit margins through increased market transparency and price comparability. These dual effects illustrate the broader structural transformation generated by digital platform economies within tourism systems.

Additional research has examined the resilience of short-term rental platforms during periods of crisis. Adamiak [16] finds that short-term rental accommodation demonstrated relatively high resilience during the COVID-19 pandemic, particularly in domestic tourism markets, partly due to the flexibility and adaptability of platform-based accommodation models. Ibănescu et al. [17] further discuss the role of collaborative economy platforms in supporting tourism resilience across EU member states during periods of market disruption.

Beyond economic performance, the expansion of platform-mediated tourism has also generated sustainability-related concerns. Nunes et al. [18] argue that dominant booking platforms may contribute to the standardization of tourism offers, potentially disadvantaging smaller local businesses and reducing destination distinctiveness in peripheral regions. Similarly, Arzoumanidis et al. [19] show that major booking platforms were relatively slow to integrate sustainability criteria into accommodation search systems, with only a limited number of eco-friendly filtering options available prior to 2020. These findings suggest that the rapid growth of digital tourism platforms has not always been fully aligned with broader sustainable tourism objectives.

2.4 Research gap

Existing research remains limited in three respects. First, much of the literature focuses on individual platforms or single-country contexts, limiting EU-wide comparative evidence. Second, harmonized Eurostat platform-generated tourism data remain underutilized in empirical tourism and IS research. Third, comparatively few studies examine whether digital booking platform activity is statistically associated with inbound tourism performance using panel econometric methods. Accordingly, this study addresses these gaps through a cross-country panel analysis of EU member states.

3. Hypotheses

Based on the existing literature on digital tourism, online booking platforms, and tourism digitalization, the present study proposes the following hypotheses:

H1: *Digital booking platform activity has a positive and statistically significant effect on inbound tourism nights across EU countries.*

Online booking platforms reduce information, search, and transaction costs while increasing destination visibility, market accessibility, and consumer convenience, thereby supporting tourism demand growth and expanding tourism distribution channels [1,7].

H2: *Internet penetration is significantly associated with inbound tourism growth across EU countries.*

Digital infrastructure facilitates access to online tourism services and supports the broader adoption of digital booking platforms and tourism-related applications. As such, internet penetration is expected to influence tourism performance, although the direction and magnitude of this relationship may vary across structurally diverse EU tourism economies depending on destination characteristics and tourism specialization [4,8].

H3: *GDP per capita is positively associated with inbound tourism growth across EU countries.*

Higher levels of economic development are generally associated with better tourism infrastructure, stronger service capacity, greater digital adoption, and increased investment in tourism-related technologies, all of which may contribute to higher tourism activity and platform market development [13,20].

4. Data and methodology

4.1 Data Sources and Samples

This study employs an unbalanced panel dataset covering the 27 European Union member states over the period 2019–2024, resulting in 153 country-year observations. All data were obtained from Eurostat using the Eurostat package in R.

The selected time period corresponds to the availability of harmonized statistics on short-term accommodation bookings through major online platforms following the data-sharing agreements established between the European Commission and Airbnb, Booking.com, Expedia Group, and Tripadvisor [2]. These agreements enabled the publication of consistent cross-country platform booking data across EU member states from 2019 onwards.

The panel is unbalanced due to incomplete reporting for several member states in 2020, mainly associated with disruptions in tourism data collection during the COVID-19 pandemic. One missing observation for internet penetration (Ireland, 2022) was imputed using the arithmetic mean of the adjacent years 2021 and 2023. Table 1 presents the variables included in the analysis, while Table 2 reports the corresponding descriptive statistics.

The dependent variable, ln(NIGHTS), measures the natural logarithm of total nights spent by non-residents in tourist accommodation establishments and serves as a proxy for

inbound tourism performance at the country level. The variable is sourced from the Eurostat dataset tour_occ_ninat.

Variable/ Symbol	Role	Description	Source	Expected Sign
Inbound tourism nights/ ln(NIGHTS)	Dependent	Total nights spent by non-residents in tourist accommodation	Eurostat, tour_occ_ninat	—
Platform bookings/ ln(PLATFORM)	Independent	Guest nights booked via online platforms (Airbnb, Booking, Expedia, Tripadvisor)	Eurostat, tour_ce_omr	+
GDP per capita/ ln(GDPPC)	Control	GDP per capita at current prices (EUR per inhabitant)	Eurostat, nama_10_pc	+
Internet penetration/ INTERNET	Control	Share of households with internet access (% of total households)	Eurostat, isoc_ci_in_h	+
Accommodation capacity/ ln(BEDS)	Control	Total bed places in tourist accommodation establishments	Eurostat, tour_cap_nat	+

Table 1. Variable Description[3]

The main independent variable, ln(PLATFORM), captures the natural logarithm of guest nights booked through major online accommodation platforms, including Airbnb, Booking.com, Expedia Group, and Tripadvisor. Sourced from the Eurostat dataset tour_ce_omr, this variable operationalizes platform-mediated tourism activity and represents the main information systems-related indicator examined in the study.

Three control variables are included in the regression framework. ln(GDPPC) measures GDP per capita at current prices (EUR per inhabitant) and controls for the level of economic development across countries. INTERNET captures the share of households with internet access and serves as a proxy for digital infrastructure and technological accessibility.

[3] Note: Data cover 27 EU member states, 2019–2024. Panel is unbalanced (N = 153) due to missing observations for nine countries in 2020.

Finally, ln(BEDS) measures the total number of bed places in tourist accommodation establishments and controls for accommodation capacity at the national level.

All continuous variables, with the exception of INTERNET, are transformed into natural logarithms in order to reduce skewness and allow coefficient interpretation in elasticity terms.

Table 2 presents the descriptive statistics for the variables included in the analysis. Considerable variation can be observed across EU member states regarding inbound tourism activity, platform-mediated accommodation bookings, and accommodation capacity, reflecting structural differences in tourism specialization and digital adoption levels. The relatively moderate skewness and kurtosis values suggest that the variables exhibit acceptable distributional properties for panel econometric analysis.

Variable	**N**	**Mean**	**Std. Dev.**	**Min**	**Median**	**Max**	**Skewness**	**Kurtosis**
ln(NIGHTS)	153	16.20	1.39	13.39	16.18	19.30	0.17	−0.71
ln(PLATFORM)	153	15.34	1.48	11.98	15.33	18.52	0.08	−0.62
ln(GDPPC)	153	10.33	0.56	9.13	10.27	11.75	0.37	−0.28
INTERNET	153	91.49	4.66	75.07	92.30	99.18	−0.84	0.61
ln(BEDS)	153	12.25	1.32	9.57	12.13	14.64	0.07	−0.64

Table 2. Descriptive Statistics[4]

Figure 1 illustrates the spatial distribution of platform-mediated accommodation bookings across EU member states during the period analyzed. The highest levels are concentrated in Mediterranean tourism-oriented economies, particularly Spain, Italy, and France, reflecting the strong integration of digital booking platforms within major inbound tourism destinations.

[4] Note: Continuous variables are reported in logarithmic form, except INTERNET, which is expressed as a percentage.

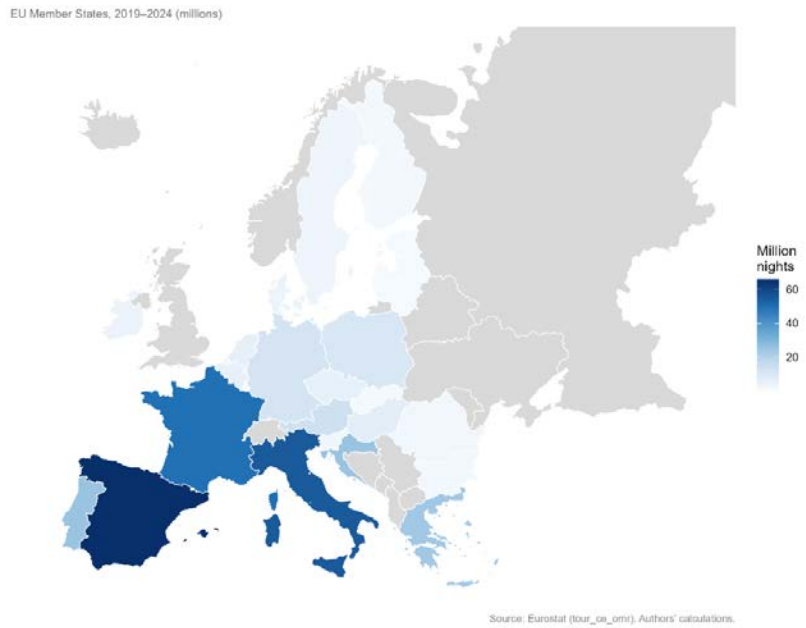


Figure 1. Spatial Distribution of Platform-Mediated Accommodation Bookings Across EU Member States (2019–2024 Average)

Table 3 presents the correlation matrix for the variables included in the analysis. The results indicate a strong positive correlation between inbound tourism nights and platform-mediated accommodation bookings ($r = 0.940$, $p < 0.001$), providing preliminary support for the expected positive association between digital booking platform activity and tourism performance.

	ln(NIGHTS)	**ln(PLATFORM)**	**ln(GDPPC)**	**INTERNET**	**ln(BEDS)**
ln(NIGHTS)	1.000				
ln(PLATFORM)	0.940***	1.000			
ln(GDPPC)	0.042	−0.053	1.000		
INTERNET	−0.020	−0.043	0.725***	1.000	
ln(BEDS)	0.851***	0.811***	−0.073	−0.049	1.000

Table 3. Correlation Matrix[5]

[5] Note: *** $p < 0.001$. High correlation between ln(GDPPC) and INTERNET ($r = 0.725$) is noted; VIF diagnostics confirm multicollinearity remains within acceptable bounds.

A similarly strong positive relationship is observed between inbound tourism nights and accommodation capacity ($r = 0.851$, $p < 0.001$).A relatively high correlation is also identified between GDP per capita and internet penetration ($r = 0.725$, $p < 0.001$), reflecting the close relationship between economic development and digital infrastructure across EU member states. However, subsequent variance inflation factor (VIF) diagnostics confirm that multicollinearity remains within acceptable limits for regression analysis.

Overall, the correlation structure provides preliminary descriptive insights into the relationships among the variables, while the multivariate panel regressions provide the main basis for hypothesis testing.

4.2 Econometric Model

The empirical analysis employs a panel data regression framework estimated using the following baseline specification:

$$\ln(NIGHTS)_{it} = \alpha + \beta_1 \ln(PLATFORM)_{it} + \beta_2 \ln(GDPPC)_{it} + \beta_3 INTERNET_{it} + \beta_4 \ln(BEDS)_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where i denotes country ($i = 1, \ldots, 27$) and t denotes year ($t = 2019, \ldots, 2024$). The term μ_i captures country-specific fixed effects, controlling for time-invariant characteristics across EU member states, such as geographic location, tourism specialization, and structural destination attributes. The term λ_t represents year fixed effects that account for common temporal shocks affecting all countries simultaneously, including the COVID-19 pandemic and the subsequent tourism recovery period. The error term is denoted by ε_{it}.

All models are estimated using the plm package in R. To evaluate the robustness of the results, four model specifications are reported: pooled OLS (Model 1), one-way fixed effects with country effects only (Model 2), two-way fixed effects including both country and year effects (Model 3), and random effects (Model 4).

The two-way fixed effects specification is considered the preferred model, as it controls simultaneously for both cross-country heterogeneity and common time-specific effects. The choice between fixed and random effects specifications was further evaluated using the Hausman test [21] (Hausman, 1978).

To address heteroskedasticity and serial correlation within panels, robust HC3 standard errors clustered at the country level are reported for the fixed effects models. In addition, variance inflation factor (VIF) diagnostics indicate that multicollinearity does not represent a significant concern, with all VIF values remaining below the conventional threshold of 5 (ln(PLATFORM) = 2.93, ln(GDPPC) = 2.11, INTERNET = 2.11, and ln(BEDS) = 2.94).

5. Results and discussion

The estimation results are presented in Table 4, which reports four model specifications: pooled OLS (Model 1), one-way fixed effects (Model 2), two-way fixed effects (Model 3), and random effects (Model 4). The Hausman test does not reject the null hypothesis of no systematic difference between fixed and random effects estimators ($\chi^2 = 5.008$, $p = 0.286$). Nevertheless, the two-way fixed effects specification with robust HC3 standard errors (Model 3) is retained as the preferred model on theoretical grounds, as it controls simultaneously for country-specific heterogeneity and common temporal shocks affecting EU member states during the study period, including the COVID-19 pandemic and the subsequent tourism recovery phase.

	(1) OLS	(2) FE One-Way	(3) FE Two-Way	(4) RE
ln(PLATFORM)	0.6830***	0.9785***	0.6879***	0.9085***
	(0.0374)	(0.0319)	(0.0693)	(0.0268)
ln(GDPPC)	0.4255***	−0.2218	0.2716	0.2850*
	(0.0831)	(0.2085)	(0.1751)	(0.1289)
INTERNET	−0.0299**	−0.0275***	−0.0169**	−0.0405***
	(0.0101)	(0.0078)	(0.0084)	(0.0066)
ln(BEDS)	0.2869***	0.1599	0.0370	0.0728
	(0.0419)	(0.2515)	(0.1788)	(0.0638)
Constant	0.5487	—	—	2.1273
	(0.7619)			(1.1507)
Observations	153	153	153	153
R^2	0.9206	0.9402	0.6362	0.9322
Adj. R^2	0.9185	0.9255	0.5274	0.9303
F-statistic	429.19***	479.24***	51.15***	1980.68***
Hausman test	—	—	χ^2= 5.008, p = 0.286	—

Table 4. Panel Regression Results — Dependent Variable: ln(NIGHTS)[6]

[6] *Note: Standard errors in parentheses. For Models 2 and 3, robust HC3 standard errors clustered by country are reported. Model 3 (two-way FE with robust standard errors) is the preferred specification. * p < 0.05; ** p < 0.01; *** p < 0.001.*

The overall fit of Model 3 is satisfactory, with an R^2 of 0.636 and an F-statistic significant at the 0.1% level, confirming the joint explanatory power of the regressors within the fixed effects framework.

Figure 2 visually illustrates the positive relationship between platform-mediated accommodation bookings and inbound tourism nights across EU member states over the 2019–2024 period. The upward trend observed across the sample is consistent with the econometric findings reported in Table 4.

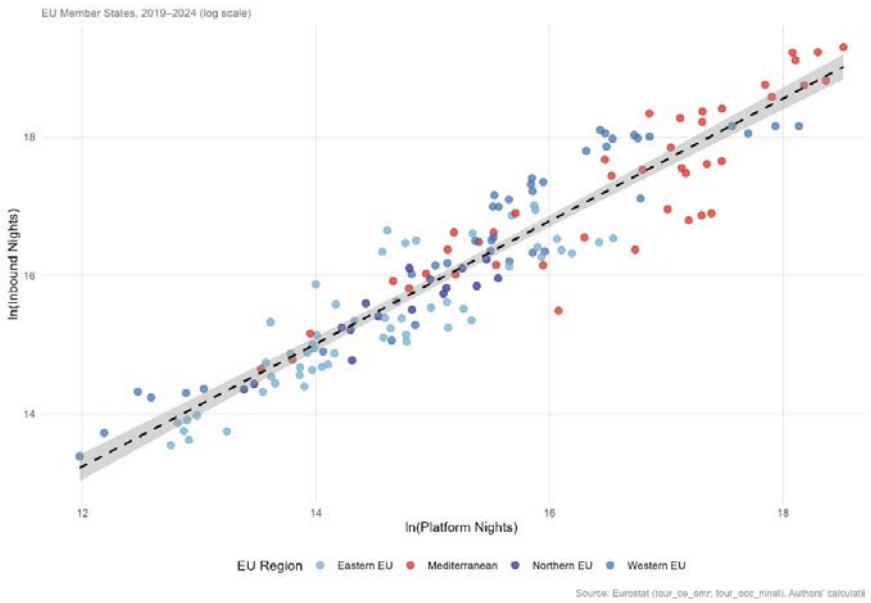


Figure 2. Relationship Between Platform-Mediated Accommodation Bookings and Inbound Tourism Nights Across EU Member States

Hypothesis 1. The coefficient of ln(PLATFORM) is positive and statistically significant across all model specifications, providing strong support for H1. In the preferred two-way fixed effects model, the estimated elasticity is 0.688 ($p < 0.001$), indicating that a 1% increase in guest nights booked through online platforms is associated with an approximately 0.69% increase in inbound tourism nights, ceteris paribus.

This finding is consistent with previous research emphasizing the role of online booking platforms in reducing transaction costs, improving destination visibility, and facilitating tourism demand growth [1,6,7]. The results further support the broader platform economy literature identifying OTAs and collaborative booking systems as important drivers of tourism market expansion across European destinations [13,14].

From an information systems perspective, the findings also highlight the analytical relevance of platform-generated tourism data as macro-level indicators capable of capturing tourism market dynamics across EU countries.

Hypothesis 2. The coefficient of INTERNET is statistically significant across all model specifications, providing support for H2. However, the estimated coefficient is negative across all models ($\beta = -0.017$, $p < 0.05$ in Model 3), indicating that the relationship between internet penetration and inbound tourism growth is more nuanced than a simple positive association.

One possible explanation is that several highly digitalized northern European economies exhibit very high levels of internet penetration while simultaneously recording lower inbound tourism intensity compared with Mediterranean tourism-oriented destinations such as Spain, Italy, Greece, and Croatia. The findings therefore suggest that digital infrastructure alone does not automatically translate into higher inbound tourism activity, particularly within structurally diverse destination economies characterized by different tourism specialization patterns.

Hypothesis 3. The coefficient of ln(GDPPC) is not statistically significant in the fixed effects specifications, although it remains positive and significant in the pooled OLS and random effects models. This pattern suggests that much of the explanatory power of GDP per capita is associated with structural cross-country differences, rather than short-term within-country variation over the study period.

The result is broadly consistent with panel data findings in tourism economics, where fixed effects specifications absorb a substantial part of the long-run structural heterogeneity across countries.

The coefficient of ln(BEDS) is not statistically significant in the fixed effects specifications, suggesting limited within-country variation in accommodation capacity over the analyzed period. However, the variable remains positive and statistically significant in the pooled OLS model, indicating that accommodation capacity continues to represent an important structural determinant of inbound tourism activity in cross-sectional comparisons across EU member states. Although a relatively strong correlation is observed between ln(GDPPC) and INTERNET, VIF diagnostics confirm that multicollinearity does not materially affect the reliability of the coefficient estimates.

Overall, the results provide empirical evidence that digital booking platform activity represents a statistically robust and economically meaningful predictor of inbound tourism growth across EU member states. The estimated platform elasticity in the preferred specification suggests that the continued expansion of platform-mediated accommodation bookings is likely to support further growth in inbound tourism activity across the European tourism market.

The findings also highlight the growing relevance of platform-generated datasets for tourism and information systems research. From a policy perspective, the continuation of institutional data-sharing initiatives between the European Commission and major online booking platforms appears justified, as harmonized platform statistics provide valuable indicators for monitoring tourism market developments at the EU level.

From an information systems perspective, the study demonstrates that platform-generated data can serve as meaningful macro-level indicators for analysing tourism system performance across countries, extending existing tourism IS research beyond individual-level adoption behaviour toward broader system-level analysis.

6. Conclusions

This study examined the relationship between digital booking platform activity and inbound tourism growth across the 27 EU member states over the period 2019–2024 using an unbalanced panel dataset and a two-way fixed effects econometric framework. The findings provide empirical evidence that digital booking platforms represent a significant component of contemporary tourism market dynamics within the European Union.

The empirical results indicate that platform-mediated accommodation bookings are positively and significantly associated with inbound tourism performance, with the preferred model suggesting an elasticity of approximately 0.69. Internet penetration also emerges as a statistically significant factor, although the negative estimated relationship highlights the structural heterogeneity of European tourism economies and suggests that digital maturity does not translate uniformly into stronger inbound tourism performance. By contrast, GDP per capita does not remain significant in the fixed effects specifications, indicating that its explanatory role is primarily associated with long-run structural differences across countries rather than short-term within-country variation.

From a theoretical perspective, the study contributes to the literature in several ways. First, it provides one of the first panel data analyses employing harmonized Eurostat platform booking statistics to examine inbound tourism performance across all EU member states. Second, it reinforces the relevance of online booking platforms as large-scale information systems capable of generating meaningful macro-level indicators for tourism analysis. Third, the findings demonstrate the analytical potential of platform-generated datasets for extending tourism information systems research beyond individual-level adoption studies toward broader system-level empirical analysis.

The study also carries practical policy implications. The positive association identified between platform booking activity and tourism performance supports the continued development of institutional tourism data infrastructures, including the maintenance and expansion of Eurostat's cooperation with major online booking platforms. At the same time, the heterogeneous effects associated with internet penetration suggest that digital

infrastructure investments may generate differentiated tourism outcomes depending on destination structure and tourism specialization across EU economies.

Several limitations should be acknowledged. The relatively short time period limits the identification of long-run dynamics, while the country-level nature of the analysis does not capture regional heterogeneity within EU member states. In addition, the possibility of endogeneity between platform activity and tourism demand cannot be fully excluded.

Future research could extend the analysis through longer time series, regional-level datasets, and additional platform-related indicators such as listing density, pricing structures, or review-based reputation measures. Further investigation of the negative relationship identified for internet penetration may also provide valuable insights into the complex interaction between digital maturity and tourism specialization across European destinations.

References

[1] Vlahović, O., Rađenović, Ž., Perović, D., Vujačić, V., & Davidović, K. *Digital Transformation in Tourism: The Role of E-Booking Systems*. Croatian Regional Development Journal, *5*(2), 129-145, 2024. https://doi.org/10.2478/crdj-2024-0012

[2] Eurostat. *Short-stay accommodation offered via online collaborative economy platforms*. Statistics Explained, 2025. Available online: https://ec.europa.eu/eurostat/statistics-explained

[3] Patrichi, I.C. *AI solutions for sustainable tourism management: A comprehensive review*. Journal of Information Systems & Operations Management, 18(1), 172–185, 2024. Available online: https://jisom.rau.ro/Vol.18%20No.1%20-%202024/JISOM%2018.1_172-185.pdf

[4] Ivancsóné Horváth, Zs., Kupi, M., & Kundi, V. *Digitalization and tourism: How X, Y, and Z generations make travel decisions in the online era.* GeoJournal of Tourism and Geosites, 60(2spl), 1302–1314, 2025. https://doi.org/10.30892/gtg.602spl26-1502

[5] European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, *Transition pathway for tourism*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2873/344425

[6] Goecke, R. *The evolution of online booking systems.* In Z. Xiang, M. Fuchs, U. Gretzel, & W. Höpken (Eds.), Handbook of e-Tourism. Springer, Cham, 2021. https://doi.org/10.1007/978-3-030-05324-6_27-2

[7] Simović, O., Rađenović, Ž., Perović, D., & Vujačić, V. *Tourism in the digital age: E-booking perspective.* ENTRENOVA - ENTerprise REsearch InNOVAtion Journal, 6(1), 616-627, 2020. Available online: https://ojs.srce.hr/entrenova/article/view/13515

[8] Bondarenko, S., Kalaman, O., & Danilova, O. *Digital transformation of the tourism business in an open economy: A comprehensive approach to travel planning and partnerships*. Social Development: Economic and Legal Issues, (4), 2025. https://doi.org/10.70651/3083-6018/2025.4.17

[9] Zaharia, R. M., Barbu, C. A., & Georgescu, C. E. *Smart Tourism and Digital Experience: Tools, Platforms and User Preferences in the Post-COVID Context*. Ovidius University Annals, Series Economic Sciences, 25(1), 2025. Available online: https://stec.univ-ovidius.ro/html/anale/ENG/2025i1/Section%204/27.pdf

[10] Cobanoglu, C., & Nizamd, A. *Determinants of online hotel booking intentions: website quality, social presence, affective commitment, and e-trust*. Journal of Hospitality Marketing & Management, 30(7), 845–870, 2021. https://doi.org/10.1080/19368623.2021.1899095

[11] Albesher, Abdulmohsen Saud, Fatimah Alhelel, and Abdul-Rahim Ahmad. *Digital information systems in hospitality: A comparative study of user feedback and rating mechanisms across booking websites*. IEEE Access , 2025 Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=11123712

[12] Patrichi, I. C. *Smart hospitality: the role of AI in enhancing sustainable guest experiences*, J. Inf. Syst. Oper. Manag., vol. 19, no. 1, pp. 241-258, 2025. Available online: https://jisom.rau.ro/Vol.19%20No.1%20-%202025/JISOM%2019.1_241-258.pdf

[13] Zeqiri, A. *From Traditional to Digital: The Evolution of Business Models in Hospitality Through Platforms*. Platforms, 2(4), 221-233, 2024. https://doi.org/10.3390/platforms2040015

[14] Mendieta-Aragón, A., Rodríguez-Fernández, L., & Navío-Marco, J. *Tourism usage of digital collaborative economy platforms in Europe: Situation, behaviours, and implications for digital policies*. Telecommunications Policy, 49(1), 102874, 2025. https://doi.org/10.1016/j.telpol.2024.102874

[15] Masri, N.W.; You, J.-J.; Ruangkanjanases, A.; Chen, S.-C.; Pan, C.-I. *Assessing the Effects of Information System Quality and Relationship Quality on Continuance Intention in E-Tourism*. Int. J. Environ. Res. Public Health 17, 174, 2020. https://doi.org/10.3390/ijerph17010174

[16] Adamiak, C. *Current state and development of Airbnb accommodation offer in 167 countries*. Current Issues in Tourism, 25(19), 3131–3149, 2022. https://doi.org/10.1080/13683500.2019.1696758

[17] Ibănescu, B.-C., Ursache, I.-M., Bejenaru, I., & Kulíš, Z. *Are collaborative economy platforms an engine for tourism resilience? Evidence from the European Union*. Eastern Journal of European Studies, 15(2), 211–230, 2024. https://doi.org/10.47743/ejes-2024-0211

[18] Nunes, J., Mata, D., Ribeiro, F., & Metrôlho, J. *Digital platforms to promote sustainable and authentic tourism in low-density territories of Southern Europe: Challenges and opportunities.* Sustainability, *17*(13), 6156, 2025. https://doi.org/10.3390/su17136156

[19] Arzoumanidis, I., Walker, A.M., Petti, L., *Online booking platforms: Towards making more sustainable choices*. Tourism Management Perspectives, 43, 100996, 2022. https://doi.org/10.1016/j.clpl.2022.100009

[20] Eurostat. *Tourism statistics — annual results for the accommodation sector*. Statistics Explained, 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Tourism_statistics_-_annual_results_for_the_accommodation_sector

[21] Hausman, J.A. Specification tests in econometrics. *Econometrica* **1978**, 46(6), 1251-1271.

Bibliography

Adamiak, C. *Current state and development of Airbnb accommodation offer in 167 countries.* Current Issues in Tourism, 25(19), 3131–3149, 2022. https://doi.org/10.1080/13683500.2019.1696758

Albesher, A.S., Alhelel, F., & Ahmad, A.-R. *Digital information systems in hospitality: A comparative study of user feedback and rating mechanisms across booking websites.* IEEE Access, 2025. Available online: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=11123712

Almeida-Santana, A., David-Negre, T., Moreno-Gil, S., *New digital tourism ecosystem: understanding the relationship between information sources and sharing economy platforms.* International Journal of Tourism Cities, Vol. 6 No. 2 pp. 335–345, 2020. https://doi.org/10.1108/IJTC-09-2019-0173

Arzoumanidis, I., Walker, A.M., Petti, L., *Online booking platforms: Towards making more sustainable choices*. Tourism Management Perspectives, 43, 100996, 2022. https://doi.org/10.1016/j.clpl.2022.100009

Bondarenko, S., Kalaman, O., & Danilova, O. *Digital transformation of the tourism business in an open economy: A comprehensive approach to travel planning and partnerships*. Social Development: Economic and Legal Issues, (4), 2025. https://doi.org/10.70651/3083-6018/2025.4.17

Capineri, C., & Romano, A. *The platformization of tourism: From accommodation to experiences.* Digital Geography and Society, 2, 100012, 2021. https://doi.org/10.1016/j.diggeo.2021.100012

Cobanoglu, C., & Nizamd, A. *Determinants of online hotel booking intentions: website quality, social presence, affective commitment, and e-trust.* Journal of Hospitality Marketing & Management, 30(7), 845–870, 2021. https://doi.org/10.1080/19368623.2021.1899095

European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. *Transition pathway for tourism*. Publications Office of the European Union, 2022. https://data.europa.eu/doi/10.2873/344425

Eurostat. *Short-stay accommodation offered via online collaborative economy platforms.* Statistics Explained, 2025. Available online: https://ec.europa.eu/eurostat/statistics-explained

Eurostat. *Tourism statistics — annual results for the accommodation sector*. Statistics Explained, 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Tourism_statistics_-_annual_results_for_the_accommodation_sector

Goecke, R. *The evolution of online booking systems*. In Z. Xiang, M. Fuchs, U. Gretzel, & W. Höpken (Eds.), Handbook of e-Tourism. Springer, Cham, 2021. https://doi.org/10.1007/978-3-030-05324-6_27-2

Hausman, J.A. *Specification tests in econometrics.* Econometrica, 46(6), 1251–1271, 1978.

Ibănescu, B.-C., Ursache, I.-M., Bejenaru, I., & Kulíš, Z. *Are collaborative economy platforms an engine for tourism resilience? Evidence from the European Union*. Eastern Journal of European Studies, 15(2), 211–230, 2024. https://doi.org/10.47743/ejes-2024-0211

Ivancsóné Horváth, Zs., Kupi, M., & Kundi, V. *Digitalization and tourism: How X, Y, and Z generations make travel decisions in the online era*. GeoJournal of Tourism and Geosites, 60(2spl), 1302–1314, 2025. https://doi.org/10.30892/gtg.602spl26-1502

Masri, N.W., You, J.-J., Ruangkanjanases, A., Chen, S.-C., & Pan, C.-I. *Assessing the effects of information system quality and relationship quality on continuance intention in e-tourism.* International Journal of Environmental Research and Public Health, 17, 174, 2020. https://doi.org/10.3390/ijerph17010174

Mendieta-Aragón, A., Rodríguez-Fernández, L., & Navío-Marco, J. *Tourism usage of digital collaborative economy platforms in Europe: Situation, behaviours, and*

implications for digital policies. Telecommunications Policy, 49(1), 102874, 2025. https://doi.org/10.1016/j.telpol.2024.102874

Nunes, J., Mata, D., Ribeiro, F., & Metrôlho, J. *Digital platforms to promote sustainable and authentic tourism in low-density territories of Southern Europe: Challenges and opportunities*. Sustainability, 17(13), 6156, 2025. https://doi.org/10.3390/su17136156

Patrichi, I.C. *AI solutions for sustainable tourism management: A comprehensive review.* Journal of Information Systems & Operations Management, 18(1), 172–185, 2024. Available online: https://jisom.rau.ro/Vol.18%20No.1%20-%202024/JISOM%2018.1_172-185.pdf

Patrichi, I.C. *Smart hospitality: The role of AI in enhancing sustainable guest experiences.* Journal of Information Systems & Operations Management, 19(1), 241–258, 2025. Available online: https://jisom.rau.ro/Vol.19%20No.1%20-%202025/JISOM%2019.1_241-258.pdf

Pencarelli, T. *The digital revolution in the travel and tourism industry*. Inf Technol Tourism **22**, 455–476 (2020). https://doi.org/10.1007/s40558-019-00160-3

Simović, O., Rađenović, Ž., Perović, D., & Vujačić, V. *Tourism in the digital age: E-booking perspective*. ENTRENOVA – ENTerprise REsearch InNOVAtion Journal, 6(1), 616–627, 2020. Available online: https://ojs.srce.hr/entrenova/article/view/13515

Srivastava, V., Dixit, I., & Duggal, R. *The Evolution of Technology in the Service Sector Concerning Hospitality*. In Transforming the Service Sector With New Technology (pp. 509-532). IGI Global Scientific Publishing. 10.4018/979-8-3693-7447-4.ch031

Vlahović, O., Rađenović, Ž., Perović, D., Vujačić, V., & Davidović, K. *Digital transformation in tourism: The role of e-booking systems*. Croatian Regional Development Journal, 5(2), 129–145, 2024. https://doi.org/10.2478/crdj-2024-0012

Zaharia, R.M., Barbu, C.A., & Georgescu, C.E. *Smart tourism and digital experience: Tools, platforms and user preferences in the post-COVID context*. Ovidius University Annals, Series Economic Sciences, 25(1), 2025. Available online: https://stec.univ-ovidius.ro/html/anale/ENG/2025i1/Section%204/27.pdf

Zeqiri, A. *From traditional to digital: The evolution of business models in hospitality through platforms*. Platforms, 2(4), 221–233, 2024. https://doi.org/10.3390/platforms2040015

Zhang, Z., & Fu, R. J. C. *Accommodation Experience in the Sharing Economy: A Comparative Study of Airbnb Online Reviews*. Sustainability, 12(24), 10500, 2020. https://doi.org/10.3390/su122410500

THE IMPACT OF AGENTIC CODING ON THE MODERN SOFTWARE DEVELOPMENT LIFECYCLE

Alexandru PÎRJAN[1]
Dana-Mihaela PETROȘANU[2]

Abstract

The evolution of Large Language Models (LLMs) has triggered a transition from stateless code completion to "Agentic Coding", where autonomous systems engage in multi-step reasoning, planning, and environment interaction. This article studies the systemic impact of this paradigm shift on the modern Software Development Lifecycle (SDLC), contrasting traditional human-centric workflows with emerging agent-augmented architectures. By conducting an in-depth framework analysis, we examine the technical structure of coding agents, focusing on ReAct patterns, multi-agent role specialization, and self-correcting feedback loops where the compiler acts as a reviewer. The study systematically evaluates implications across the SDLC, detailing how agents accelerate requirements engineering through automated prototyping and how they are revolutionizing quality assurance via self-healing test suites. The integration of autonomous agents is not without friction as the analysis highlights a dichotomy between increased implementation velocity and the degradation of long-term maintainability. We identify extremely important risks, including security vulnerabilities arising from hallucinated dependencies and the cognitive load associated with reviewing complex, machine-generated logic. Economically, the shift suggests a complex trade-off between operational token costs and developer productivity gains. Conclusively, the study demonstrates that Agentic Coding demands a redefinition of the developer's role from syntax author to system coordinator. We consider that realizing the full potential of this technology requires rigorous new standards in formal verification and a restructuring of computer science education to prioritize architectural oversight over routine implementation.

Keywords: Agentic Coding, Software Development Lifecycle (SDLC), Large Language Models (LLMs), Autonomous Agents, ReAct Pattern, Human-in-the-Loop, Code Maintainability, DevOps Automation

JEL Classification: O3, O33, O34, O35, O36, O38

1. Introduction

The software engineering landscape is currently undergoing a transformation of a magnitude comparable to the advent of high-level compilers or to the introduction of object-

[1] PhD Hab. Full Professor, School of Computer Science for Business Management, Romanian-American University, 1B, Expozitiei Blvd., district 1, code 012101, Bucharest, Romania, alexandru.pirjan@rau.ro
[2] PhD Lecturer, Department of Mathematics-Informatics, National University of Science and Technology Politehnica Bucharest, 313, Splaiul Independentei, district 6, code 060042, Bucharest, Romania, dana.petrosanu@upb.ro

oriented programming. At the heart of this transformation is the evolution of LLMs [1,2], which has triggered a decisive transition from simple, stateless code completion to a new operational paradigm known as "Agentic Coding" [3–6]. In order to understand the significance of this shift, one must first distinguish between the capabilities of previous generations of AI assistance and the emerging autonomous systems. Traditional code assistants [7–9], often referred to as "Copilots", operate primarily as advanced stochastic predictors [8–10]. They are stateless entities that predict the next likely token based on a static window of preceding text [4,11]. While effective at reducing repetitive code ("boilerplate"), these systems lack an intrinsic understanding of the broader system state, the result of code execution, or the interdependencies across a complex file tree [7,12].

1.1. Defining Agentic Coding Beyond Autocomplete and Copilots

Agentic Coding represents a fundamental departure from this passive model. In this case, autonomous systems are capable of engaging in multi-step reasoning, strategic planning, and active interaction with the development environment [3–6]. Unlike a text-predictor that suggests a function body and ceases operation, a coding agent perceives the codebase as a mutable environment [3,4,11,13–17]. It uses specific architectural frameworks to decompose high-level instructions into discrete tasks, executes terminal commands in order to verify its outputs, and interprets compiler error messages in order to iteratively refine its solution [3,14,15,18]. This cyclical process of action and observation allows the agent to manage the development lifecycle with a degree of autonomy which had been previously reserved for human engineers.

The distinction consists in the capacity for self-correction and goal-oriented behavior [3,4,11]. Where a Copilot requires the human to identify a bug and prompt for a fix, an agentic system can run a test suite, observe the failure, hypothesize a correction, apply the patch, and re-run the test to confirm validity [7–9]. This capability relies heavily on ReAct ("Reasoning and Acting") [13,19–22] patterns and self-correcting feedback loops [23] where the compiler effectively acts as an automated reviewer [3,6,24,25]. Consequently, Agentic Coding represents a broader transformation of the development process, redefining how code is being produced, validated, and incorporated, therefore relocating decision-making from syntax-level micro-management to goal-level coordination [3,4,11].

1.2. The Paradigm Shift from Human-Centric to Agent-Augmented Development

The introduction of autonomous agents into the software production line leads to a profound systemic impact on the modern SDLC, requiring a reevaluation of workflows that have traditionally been strictly human-centric. We are witnessing a migration from a workflow where the human developer is the sole author and architect, using tools merely for assistance, to an agent-augmented architecture where the human acts as a supervisor or "human-in-the-loop" [3–5,11,16,26]. This sociological and operational shift redefines the primary bottleneck of software production. In the traditional model, the speed of development has been limited by the human cognitive capacity to synthesize logic into syntax. In the agent-augmented model, the constraint shifts to the human capacity to review, audit, and integrate machine-generated logic.

This integration of autonomous agents is not without friction, presenting a complex trade-off between velocity and stability. While agents can dramatically accelerate the implementation phase, creating a surge in code volume, this creates a new class of challenges regarding the long-term maintainability of the software [3,15,18]. The analysis highlights a critical dichotomy, namely the increase in implementation velocity often correlates with a degradation of maintainability, a phenomenon termed the "drift" of human context [4,13,14,18,27,28]. As agents generate vast quantities of code autonomously, the human developer's mental model of the system, the "context" begins to erode [29]. When developers are no longer the primary authors of the codebase, their intimate understanding of its structure erodes, impairing rapid debugging and long-term architectural changes.

Furthermore, this paradigm shift imposes a heavy cognitive load associated with reviewing complex, machine-generated logic, which may not always align with human readability standards. The developer's role is forcibly redefined from that of a syntax author to a system coordinator, responsible for managing multiple agents rather than writing loops and conditionals. This transition fundamentally alters the economics of development as well, suggesting a complex trade-off between operational token costs, the price of running the models and the gains in developer productivity [4,29,30]. Ultimately, the shift to Agentic Coding extends beyond just a technical upgrade, reshaping the labor structures and cognitive workflows that define software engineering.

1.3. Research Objectives and Scope

The primary objective of this study is to systematically evaluate the implications of Agentic Coding across the entire SDLC in order to provide a structured analysis of this emerging technology. We aim to contrast traditional human-centric workflows with emerging agent-augmented architectures in order to isolate exactly where value is being created and where risk is being introduced. An important focus of this research is to conduct an in-depth framework analysis of the technical structure of coding agents, specifically examining how ReAct patterns and multi-agent role specialization enable autonomous problem solving. We seek to understand the mechanics of self-healing test suites and how the compiler serves as a feedback mechanism for iterative refinement.

Furthermore, this article intends to critically assess the risks associated with passing code generation down to autonomous systems. We have identified extremely important risks, including security vulnerabilities arising from hallucinated dependencies where agents invent non-existent software packages up to the previously mentioned cognitive load placed on human reviewers. The scope of our research also extends to the economic viability of this approach, namely analyzing the trade-offs between the financial cost of inference (tokens) and the reduction in human hours required for routine tasks.

We consider that attaining the full potential of this technology requires more than just better models, it demands a restructuring of computer science education and the adoption of rigorous new standards in formal verification. By detailing how agents accelerate requirements engineering through automated prototyping and revolutionize quality assurance, this study aims to provide a comprehensive roadmap for industry practitioners and academic researchers as they transition to autonomous software development.

1.4. Structure of the Paper

The remainder of this scientific article is organized to provide a logical progression from historical context to future implications. Section 2 traces the evolution of AI in software engineering, distinguishing the capabilities of modern agents from early static analysis tools and predictive LLMs. Section 3 details the architectural framework of coding agents, exploring core components such as context windows, memory systems, and the mechanisms of tool use and environment interaction. Section 4 constitutes the core contribution of the paper, offering a granular analysis of the impact of agentic coding on each phase of the SDLC, from requirements engineering and design up to implementation, testing, and deployment. Section 5 provides a quantitative and qualitative impact analysis, discussing productivity metrics and the economic shifts inherent in this new model. Section 6 addresses the critical challenges and risks, including security vulnerabilities and the "drift" of human context. Section 7 discusses the transforming role of the human developer, while Section 8 outlines future directions such as the integration of formal verification methods. Finally, Section 9 concludes the study with a summary of key findings and recommendations for industry adoption.

2. The Evolution of AI in Software Engineering

The trajectory of software engineering tools has historically followed a path of increasing abstraction, moving from binary machine code to high-level languages, and eventually to complex development environments [31,32]. The software engineering field is undergoing a transformation of a magnitude comparable to the advent of high-level compilers or to the introduction of object-oriented programming. In order to understand the specific impact of "Agentic Coding", it is necessary to contextualize it within the broader history of automated development tools. This evolution encompasses a distinct progression from deterministic, rule-based heuristics to stochastic code completion, and finally, to the emerging era of autonomous agents capable of reasoning and environment interaction [11,31,32].

2.1. Historical Context of Static Analysis, IntelliSense, and Early Heuristics

Before the advent of probabilistic models, the automation of software development was grounded in deterministic algorithms and rigid rule sets. Early tools focused primarily on syntax verification and static analysis, operating within strictly defined boundaries [32,33]. These systems used Abstract Syntax Trees (ASTs) to parse code and identify deviations from established language standards or logical errors that could be detected without execution [24,32,33]. While these tools were very important in ensuring code quality, they were fundamentally passive. They could flag a syntax error but possessed no capability to understand the intent behind the code or to generate logic autonomously.

The introduction of "IntelliSense" and similar code-completion technologies marked a significant step forward, but they remained heuristic in nature [34]. These tools operated by indexing the codebase and offering suggestions based on type definitions and function signatures. This significantly reduced the cognitive load required for syntax recall,

effectively positioning the developer as the sole author and architect who used tools merely for assistance. In this traditional model, the speed of development was limited strictly by the human cognitive capacity to synthesize logic into syntax. The tools were unable of "hallucination" [1–4,35,36] because they were constrained by the finite set of symbols available in the project libraries, but they were equally unable of creativity or adaptation. They represented a human-centric workflow where the engineer micro-managed every line of code. This era established the foundational labor structures where the developer was responsible for writing loops and conditionals, an approach that remained largely unchallenged until the integration of statistical learning models [1–4,14,32].

2.2. The Rise of LLMs in Code Generation

The integration of LLMs [1,2] into the software domain triggered a decisive transition from simple, stateless code completion to more fluid generative capabilities. This phase, characterized by the proliferation of "Copilots", introduced tools that operate primarily as advanced stochastic predictors [7–9]. Unlike their rule-based predecessors, these models use the "Transformer" architecture [1,2] to analyze vast repositories of open-source code, allowing them to predict the next likely token based on a static window of preceding text [4,11]. This statistical approach allowed for the generation of entire function bodies and the reduction of repetitive "boilerplate" code.

Nevertheless, despite their generative power, these systems function as stateless entities [4,11]. A Copilot suggests a snippet of code based on immediate context but ceases operation the moment the suggestion is accepted. It lacks an intrinsic understanding of the broader system state, the result of code execution, or the interdependencies across a complex file tree. The interaction remains strictly synchronous and human-initiated, namely the human must identify a need, prompt the model, review the output, and manually integrate it. If the generated code introduces a bug, the model is unaware of the failure unless the human explicitly prompts for a fix. Consequently, while LLMs increased the velocity of syntax production, they did not alter the fundamental agency of the developer. The developer remained the active driver, while the AI served as a high-speed, although occasionally an unreliable engine. This limitation needed a shift toward systems that could maintain context and act autonomously, which led to the emergence of Agentic Coding [3,11,13,14,37,38].

2.3. Emergence of Autonomous Agents for Planning, Reasoning, and Execution

The current frontier of software engineering is defined by "Agentic Coding" [3–6] which represents a fundamental departure from the passive model of text prediction. In this approach, autonomous systems engage in multi-step reasoning, strategic planning, and active interaction with the development environment. Whereas a token-based completion model typically generates a snippet and terminates execution, a coding agent conceptualizes the repository as an evolving, actionable workspace mutable environment [3,4,11,13–17]. This capability is achieved through specific architectural frameworks, most notably the ReAct [13,19–22] patterns, which enable the system to decompose high-level instructions into discrete tasks.

The defining characteristic of these agents is their capacity for self-correction and goal-oriented behavior [3,4,11]. The agent interacts with the development environment by executing terminal commands for verification and by interpreting compiler errors to improve the implementation through successive iterations. This cyclical process of action and observation allows the agent to manage the development lifecycle with a degree of autonomy previously reserved for human engineers. For instance, where a "Copilot" requires the human to spot a failure, an agent can run a test suite, observe the failure, hypothesize a correction, apply the patch, and re-run the test to confirm validity.

This introduces self-correcting feedback loops [23] where the compiler effectively acts as an automated reviewer. The implication is a systemic shift in the SDLC, detailing how agents accelerate requirements engineering through automated prototyping and revolutionize quality assurance [39–41] via self-healing test suites [3–5,12,14]. Nevertheless, this autonomy introduces new risks, such as the "drift" of human context, where the human developer's mental model of the system begins to erode as agents generate vast quantities of code [4,13,14,18,27,28]. The developer is no longer the author of every line and therefore loses the intimate familiarity required for rapid debugging. Consequently, the emergence of agents demands a redefinition of the developer's role from syntax author to system coordinator.

2.4 Comparative analysis between Assisted Coding and Agentic Coding

In order to fully appreciate the implications of this technological shift, it is very important to distinguish between the capabilities of previous generations of AI assistance and emerging autonomous systems (Figure 1).

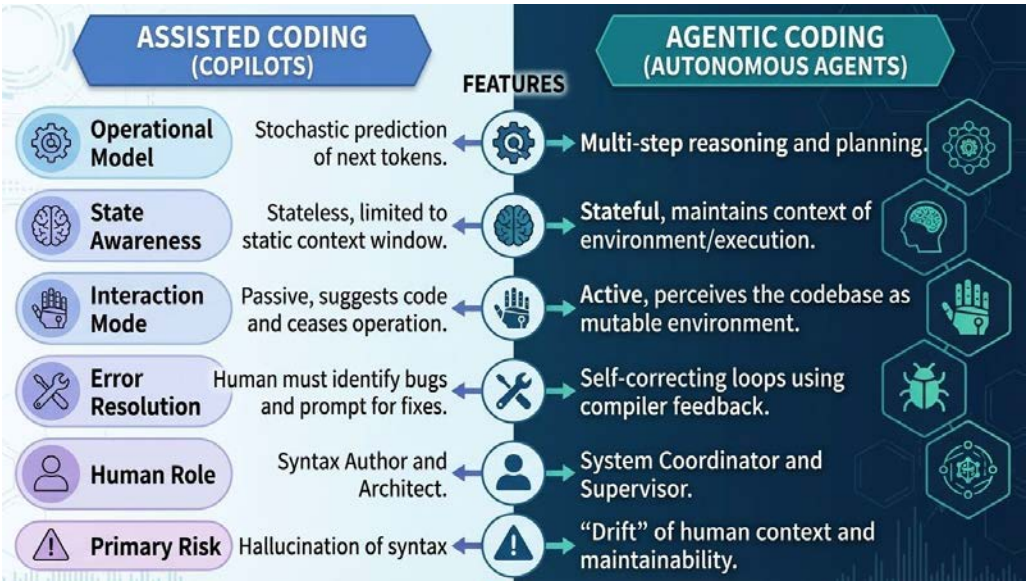


Figure 1: Structural comparison between Assisted Coding and Agentic Coding

This transition reflects an expansion in operational scope and autonomy, alongside improvements in accuracy. While assisted coding focuses on increasing the speed of typing and syntax retrieval, "Agentic Coding" relocates decision-making from syntax-level micro-management to goal-level coordination [17,38]. This distinction fundamentally changes the economics of development, suggesting a complex trade-off between operational token costs and developer productivity gains [4,29,30].

3. Architectural Framework of Coding Agents

The transition from stochastic text prediction to autonomous software engineering requires a complex architectural restructuring that extends far beyond the capabilities of the underlying LLM [1,2]. While the LLM serves as the cognitive engine, providing the reasoning capabilities and semantic understanding of code, it is the surrounding architectural framework that enables agentic behavior. This framework transforms a passive request-response system into a stateful, goal-oriented [3,4,11] entity capable of manipulating the software environment. In this section, we analyze the elements of a coding agent, examining the mechanisms that allow for long-term memory retention [3,4,11,29], active environment interaction [3,4,11,13–17], multi-agent collaboration [3,4,11,14,16–18,26], and the extremely important feedback loops [23] that drive iterative self-correction.

3.1. Core Components of Coding Agents (LLMs, Context Windows, and Memory Systems)

At the nucleus of the agentic framework lies the LLM [1,2], which functions less as a database of knowledge and more as a reasoning engine capable of syntactic synthesis and logical deduction. Nevertheless, the efficacy of the LLM in a software development context is fundamentally constrained by its context window, namely the finite limit of tokens the model can process at any single instant. In complex software projects, which often span hundreds of files and millions of lines of code, the entirety of the system state cannot fit within this immediate operational memory [29]. Consequently, the architecture of a coding agent must implement robust memory systems that mitigate the limitations of the model's stateless operation while supporting the long-running requirements of the development lifecycle.

In order to overcome the transient nature of the context window, agentic architectures use a dual-memory approach comprising short-term working memory and long-term archival storage [3,4,11,29]. Working memory is strictly managed to contain the immediate problem context, such as the active file being edited, relevant function definitions, and the current set of instructions. Because the model predicts tokens based on a static window of preceding text [4,11], optimizing this window is extremely important for maintaining logical coherence. If irrelevant data saturates the window, the model suffers from "distraction" leading to hallucinations [1–4,35,36] or loss of the original directive. Therefore, agents employ dynamic context pruning, selectively summarizing or discarding information that is no longer strictly relevant to the immediate reasoning step [3,4,11,17,18].

Long-term memory is typically implemented through Vector Databases and Retrieval-Augmented Generation (RAG) [8,42] techniques. Instead of attempting to load the entire codebase into the context window, the agent generates vector embeddings, namely numerical representations of semantic meaning, for every function, class, and documentation file in the project. When tasked with a modification, the agent queries this vector database in order to retrieve only the snippets of code that are semantically relevant to the current objective. This allows the agent to maintain an understanding of system-wide interdependencies without being overwhelmed by raw data. By decoupling the reasoning engine from the storage mechanism, the architecture grants the agent a form of infinite pseudo-memory [3,4,11,29], enabling it to respect architectural patterns established in modules that had been created months prior. This stateful awareness is the primary differentiator between a standard Copilot, which sees only the opened file, and an agent that "understands" the broader repository [3,4,7–9,16–18,26].

3.2. Tool Use and Environment Interaction (IDEs, CLIs, Version Control)

While memory systems [3,4,11,29] provide the context required for reasoning, it is the capacity for tool use and environment interaction that transforms that reasoning into tangible software artifacts. Within an agentic coding approach, the codebase functions as a modifiable environment [3,4,11,13–17] accessed via specific interfaces, not merely as a fixed text artifact. The architecture defines a schema of "tools", namely executable functions that the LLM can invoke to perform actions outside its neural network [3–6]. These tools provide an interface between Natural Language Processing [43]and the deterministic operating system, allowing the agent to function as a digital operator.

The most fundamental interaction capability is File I/O [3,4], which grants the agent the permission to read directory structures, open files, and write changes to disk. Nevertheless, advanced agentic frameworks go beyond simple text manipulation by integrating directly with the Command Line Interface (CLI) [3,4,7–9,16–18,26]. This allows the agent to execute terminal commands, a very important capability for verifying the validity of its own work. For instance, an agent acts by creating a new branch in the version control system, installing dependencies via a package manager, or running a build script to check for compilation errors. This interaction is bidirectional, namely the agent issues a command, and the environment returns the standard output (stdout) or standard error (stderr), which the agent then processes as new observation data [3,13].

Furthermore, complex agents integrate with the Language Server Protocol (LSP) [4,5,18,44], the same technology that powers modern Integrated Development Environments (IDEs). By querying the LSP, an agent can request the definition of a symbol, find all references to a function, or view type signatures without needing to "read" every file textually. This mimics the workflow of a human developer who goes through a codebase using "Go to Definition" features rather than scrolling linearly. This structural understanding is extremely important for refactoring tasks, where changing a variable name in one location requires precise updates across multiple dependencies. By leveraging these tools, the agent moves beyond the passive suggestion of code and engages in active construction, managing the environment with a degree of autonomy specific for human

engineers. The environment essentially becomes the "world" in which the agent operates, and the tools are the effectors through which it exerts change.

3.3. Multi-Agent Systems' Specialized Roles (Architect, Coder, Reviewer)

As the complexity of software tasks increases, the performance of a single monolithic agent tends to degrade. The cognitive load required to simultaneously maintain the high-level architectural vision, write syntactically correct code, and audit for security vulnerabilities often leads to context drift and hallucination [4,13,14,18,27,28]. In order to mitigate this, modern agentic frameworks employ Multi-Agent Systems (MAS) [3,4,11,14,16–18,26], where the workload is decomposed and distributed across specialized synthetic personas. This architecture mimics the structure of a human software development team, assigning distinct roles and responsibilities to different instances of the model.

In a typical multi-agent configuration [3,4,11,14,16–18,26], a high-level "Architect" agent is responsible for the initial decomposition of the user's prompt. Rather than producing implementation code, it decomposes the feature request into discrete, logical steps and specifies the interfaces between them. This plan is then passed to a "Coder" agent, whose sole focus is the implementation of the specific sub-task within the constraints defined by the Architect. By narrowing the scope of the Coder agent, the architecture reduces the probability of error and ensures that the generated code adheres to the project's established patterns.

Extremely important, the workflow includes a "Reviewer" or "Critic" agent that acts as a quality gate [3,4,11,14,16–18,26]. After the "Coder" submits a solution, the "Reviewer" evaluates it for syntactic correctness, logical validity, security issues, and compliance with the planned design. This "Reviewer" operates with a different system prompt, one primed to be skeptical and analytical rather than generative. If the "Reviewer" detects a potential issue, such as a hallucinated dependency [1–4,35,36] or a violation of the "Single Responsibility, Open-Closed, Liskov Substitution, Interface Segregation, and Dependency Inversion" (SOLID) [45–47] principles, it rejects the submission and provides feedback to the "Coder", triggering a refinement loop. This separation of concerns prevents the "blind spots" that occur when a single entity reviews its own work. The human developer, in this scenario, shifts from being the primary author to being the "System Coordinator", overseeing the interaction between these agents and intervening only when the consensus between them breaks down. This role specialization ensures that while one agent focuses on the details of syntax, another retains the "context" of the broader system, preventing the erosion of architectural integrity [4,13,14,18,27,28].

3.4. Feedback Loops for Self-Correction and Iterative Refinement

The defining characteristic of Agentic Coding, which distinguishes it sharply from the stochastic prediction of Copilots, is the implementation of rigorous feedback loops [3–6,23]. A Copilot operates in an open loop, it suggests code, and if that code is flawed, the system remains unaware unless a human explicitly intervenes. In contrast, autonomous agents operate in a closed loop driven by the ReAct [13,19–22] pattern, where the output

of an action is immediately observed and evaluated in order to inform the next step. This cyclical process is what enables self-correction and iterative refinement.

The most potent feedback mechanism in this framework is the usage of the compiler or interpreter as an objective critic. When an agent generates code it attempts to compile or execute it within a sandboxed environment. If the compiler returns an error, the agent captures the error message, parses it to understand the nature of the failure (e.g., a type mismatch or a syntax error), and uses this data to hypothesize a correction. This "Compiler-as-Critic" loop allows the agent to fix low-level issues autonomously [3,4,11,14,16–18,26], ensuring that the code presented to the human is, at the very least, syntactically valid.

Beyond compilation, agents are increasingly capable of generating and running their own test suites. Upon implementing a feature, the agent writes a corresponding unit test, executes it, and observes the result [3,5,11,24]. If the test fails, the agent engages in a diagnostic process, it determines whether the implementation is incorrect or if the test case itself is flawed. It then applies a patch and re-runs the test to confirm validity. This capability creates a self-healing system [3–5,12,14] where the software is continuously validated against its functional requirements during the generation process. By integrating these feedback loops [23], the architectural framework shifts the burden of error resolution from the human to the machine, redefining the development workflow from manual debugging to supervisory approval. This iterative capacity is the technical foundation that supports the broader systemic impact of agents on the SDLC, enabling the shift from human-centric authorship to agent-augmented coordination.

4. Impact on the SDLC

The integration of autonomous agents into the software production line leads to a profound systemic impact on the modern SDLC, calling for a systematic review of workflows that have, until now, been predominantly human-driven. As outlined in the introductory analysis, this technology affects more than a localized efficiency boost by fundamentally changing the labor structures and cognitive workflows that define software engineering. The transition from a workflow where the human developer is the sole author and architect to an agent-augmented architecture affects every phase of production, from the initial elicitation of requirements to the final operational deployment. This section provides a granular analysis of these shifts, contrasting traditional methodologies with emerging agentic behaviors to isolate exactly where value is being created and where risk is being introduced.

4.1. Requirements Engineering and Planning

The initial phase of the SDLC, typically characterized by high ambiguity and human-to-human negotiation, is undergoing a significant transformation through the application of Agentic Coding [5,14,16]. Traditionally, requirements engineering has been a manual process of translation, where business logic is slowly converted into technical specifications through iterative meetings and documentation [14,32]. The introduction of agents

accelerates this phase by automating the prototyping of requirements, allowing for a more dynamic interaction between abstract intent and concrete specification.

In the agent-augmented model, the "Architect" agent plays an extremely important role in in translating user prompts into clear, actionable technical requirements. Unlike traditional static analysis tools that require formal syntax [24,32,33], agentic systems possess the semantic understanding necessary to decompose high-level instructions into discrete, logical tasks. When a stakeholder provides a vague functional description, the agent records it and very important, it actively interrogates the request by generating a preliminary requirements document. This process relies on the multi-step reasoning capabilities inherent in the ReAct [13,19–22] pattern, enabling the system to identify missing parameters or logical inconsistencies within the initial prompt.

Consequently, the role of the human operator shifts from writing the specification to reviewing the agent's interpretation of the business need. This rapid feedback loop [3–6,23] ensures that architectural misunderstandings are caught early in the lifecycle, well before implementation begins. The agent leverages its training on vast repositories of open-source code to suggest standard compliance requirements and security protocols that a human author might overlook during the initial drafting. By converting natural language directly into structured technical schemas, agents reduce the cognitive load associated with the "blank page" problem [32,48,49], allowing engineers to refine a generated baseline rather than constructing specifications from scratch.

Beyond sheer text generation, autonomous agents contribute to the planning phase by performing preliminary feasibility analyses. Because these agents perceive the codebase as a mutable environment [3,4,11,13–17] and can access file trees and dependency graphs, they can instantly cross-reference a new feature request against the existing system architecture. If a proposed requirement contradicts an established design pattern or requires a dependency that introduces known security vulnerabilities, the agent can flag this risk immediately.

This capability transforms technical roadmapping from a speculative exercise into a data-driven process. The agent can simulate the implementation path, effectively identifying the "interfaces between them" and planning the necessary modifications to the file structure. This predictive capacity is supported by the agent's ability to retrieve semantically relevant code snippets via Vector Databases [8,42], ensuring that the planning process respects the architectural patterns established in modules created months prior. Therefore, the feasibility analysis becomes a continuous, automated background process rather than a distinct milestone, allowing for a more agile response to changing business requirements.

4.2. Design and Architecture

The design phase has historically been the domain of senior human engineers, relying heavily on intuition and experience. The emergence of multi-agent systems [3,4,11,14,16–18,26] with specialized roles, such as the "Architect" and "Reviewer", suggests that even high-level design decisions can be augmented by artificial intelligence.

One of the most immediate impacts of Agentic Coding on the design phase is the collapse of the distinction between design and prototyping [3–6,14]. In a traditional workflow,

creating a prototype is a labor-intensive task that often results in "throwaway" code. In contrast, an agent can generate a functional prototype by decomposing the feature request into sub-tasks and executing them. This allows stakeholders to interact with a working model of the software almost immediately after the requirements have been defined.

This acceleration is facilitated by the agent's ability to handle "boilerplate" code and standard architectural setups, freeing the human architect to focus on novel logic. The agent acts as a force multiplier, rapidly instantiating the initial structure of the application based on best practices retrieved from its training data. This capability allows for "exploratory coding", where multiple architectural approaches can be implemented and compared in parallel [4,14,16,18,21,26], a luxury that time constraints rarely permit in human-only teams. The result is a design process that is empirical rather than theoretical, namely decisions are based on the observed performance of generated prototypes rather than abstract diagrams.

While agents are capable of generating code, the "Architect" agent is specifically designed to maintain the high-level vision and prevent the erosion of architectural integrity [4,13,14,18,27,28]. When a human developer considers a structural change, the agent can serve as a complex decision support system. By analyzing the entire repository through its long-term memory systems [3,4,11,29], the agent can predict the ripple effects of a proposed architectural change across the complex file tree.

This systemic awareness addresses the "drift" of human context [4,13,14,18,27,28], a critical risk where the developer loses the intimate familiarity required for architectural evolution. The agent provides a counter-balance by surfacing relevant dependencies and enforcing "SOLID" [45–47] principles during the design review. It essentially acts as a guardian of the system's structural health, offering recommendations to refactor tightly coupled components or to introduce abstraction layers where necessary. This collaboration allows the human engineer to operate at a higher level of abstraction, coordinating the system's evolution while the agent manages the granular details of component interaction.

4.3. Implementation (Coding)

The implementation phase is where the impact of Agentic Coding is most visible and arguably most disruptive. The transition from stateless code completion to stateful, goal-oriented agents fundamentally alters the economics and mechanics of writing code [4,29,30].

The introduction of agents creates a surge in code volume, dramatically accelerating the implementation phase [3,13,14]. Agents can generate vast quantities of code autonomously, effectively removing the human typing speed as a limiting factor in production. Nevertheless, this increase in velocity presents a contrast, namely while the output in terms of "Lines of Code" (LOC) increases, the metric of "throughput" (defined as the delivery of verified, valuable features) becomes constrained by the human's capacity to review the code.

The bottleneck of software production shifts from the cognitive capacity to synthesize logic into syntax to the capacity to audit machine-generated logic. As agents are handling the routine implementation of loops, conditionals, and standard algorithms, the human

developer is being inundated with code that they did not write. This aspect needs a shift in performance metrics from raw code generation to the efficiency of the review and integration process. The sheer volume of produced code can lead to a bloated codebase [50,51] if not rigorously managed, highlighting the trade-off between operational token costs and developer productivity gains.

A very important challenge in the implementation phase consists in the difference between syntactic correctness and semantic validity. Agents, using the "Compiler-as-Critic" loop [3,4,11,14,16–18,26], are highly effective at producing code that compiles and runs without throwing syntax errors. They can parse error messages and hypothesize corrections autonomously. Nevertheless, syntactic perfection does not equate to semantic accuracy.

An agent may generate a function that is mathematically sound and bug-free but completely misaligns with the broader business intent or with the existing domain logic. This is a manifestation of the "drift" of human context, where the machine's localized reasoning diverges from the global system goal [4,13,14,18,27,28]. The "Reviewer" agent attempts to mitigate this by evaluating logic against the planned design, but the ultimate responsibility remains with the human-in-the-loop to ensure that the code "means" what it is supposed to mean [3,4,11,14,16–18,26]. The cognitive load associated with reviewing this complex, machine-generated logic is significant, as understanding code written by another entity (synthetic or human) is often harder than writing it oneself.

One of the most promising applications of Agentic Coding in the implementation phase is the refactoring of legacy systems. Legacy codebases are often characterized by low readability and high complexity, making them difficult for humans to modify without introducing regressions. Agents, equipped with vector embeddings of the entire project [8,42], can analyze these opaque systems to identify redundancy and inefficiency.

By integrating with the Language Server Protocol (LSP) [4,5,18,44], agents can perform precise refactoring operations, such as renaming variables across multiple files or extracting methods to improve modularity. Unlike a human who might miss a reference, the agent uses the deterministic tools of the development environment [3,4,11,13–17] to ensure comprehensive updates. This capability allows organizations to modernize technical debt [32,52] at a scale that would be cost-prohibitive with human labor alone. The agent effectively "reads" the legacy code, constructs a conceptual model of its functionality, and rewrites it to adhere to modern standards, all while verifying the changes through the execution of terminal commands.

4.4. Testing and Quality Assurance

The domain of Quality Assurance (QA) [39–41] represents an area where Agentic Coding offers significant technical advancements. The ReAct [13,19–22] pattern integrates testing into the generative process rather than leaving it as a separate verification stage.

In the agent-augmented SDLC, the generation of code is inextricably linked to the generation of tests. When a "Coder" agent implements a feature, it is simultaneously tasked with writing the corresponding unit and integration tests [3,4,11,14,16–18,26]. This ensures that every line of machine-generated code is immediately subjected to verification. The

agent analyzes the control flow of the generated function, identifying edge cases and boundary conditions that require coverage [3,4,28].

This autonomous generation extends to the creation of mock objects and test fixtures, tasks that are typically tedious for human developers. By querying the vector database [8,42] for existing test patterns, the agent ensures that new tests maintain consistency with the project's testing strategy. This anticipatory approach to QA [39–41] shifts the culture from "testing quality in" at the end of the cycle to building it in during the implementation, effectively preventing the accumulation of untested logic.

A defining characteristic of agentic systems is the capability for self-healing test suites [3–5,12,14]. In traditional development, a change in the codebase often breaks existing tests, requiring manual intervention to update the test logic. An autonomous agent, however, can observe a test failure, analyze the assertion error, and determine whether the failure is due to a bug in the application or a mismatch in the test expectation.

If the test is outdated, the agent can rewrite the test script to align with the new functionality. If the application code is at fault, the agent enters a self-correcting loop, namely it hypothesizes a fix, applies the patch, and re-runs the test to confirm validity [3,4,11,14,16–18,26]. This "closed loop" operation creates a robust defense against regression [4,23,28], allowing the test suite to evolve organically alongside the application. It significantly reduces the maintenance burden of QA automation [39–41], which is often a primary cause of test abandonment in legacy projects.

Beyond unit testing, agents are revolutionizing the debugging process through automated reproduction. When a bug is reported, an agent can be tasked with creating a reproduction script that isolates the failure. By interacting with the CLI and analyzing the standard error (stderr) output, the agent can iterate on inputs until the crash or logical error is replicated [3,4,11,14,16–18,26].

This capability is particularly valuable for complex, state-dependent bugs that are difficult for humans to trace. Once the bug is reproduced and captured in a test case, the agent can leverage its reasoning engine to identify the root cause within the file tree. The agent effectively automates the scientific method of debugging through observation, hypothesis, experimentation, and verification, therefore freeing the human developer to focus on high-level system stability rather than transient error resolution.

4.5. Deployment and Operations

The final stage of the SDLC, deployment and operations, benefits from the agent's ability to interact directly with the development environment and infrastructure tools.

Agents treat infrastructure configuration with the same rigor as application code [53,54]. By generating and managing "Infrastructure as Code" (IaC) scripts (e.g., Terraform or Kubernetes manifests) [4,5,14,16], agents can provision resources and configure environments autonomously. The "Architect" agent can specify the necessary infrastructure based on the application's requirements, and the "Coder" agent can generate the corresponding configuration files.

This automation reduces the risk of configuration drift, as the agent ensures that the deployed environment matches the defined specifications [4,13,14,18,27,28]. Furthermore, agents can validate these configurations by executing "dry runs" or validation commands via the terminal, ensuring that syntax errors in the infrastructure definitions are caught before deployment. This extends the "Compiler-as-Critic" approach [3,4,11,14,16–18,26] to the domain of operations, creating a safer and more predictable deployment pipeline.

In the context of Continuous Integration and Continuous Deployment (CI/CD) [53–56], agents act as intelligent operators of the pipeline. They can analyze build logs to diagnose failure causes, distinguishing between transient network issues and genuine code defects. Upon detecting a build failure, the agent can automatically revert the respective commit or attempt a "fix-forward" strategy by applying a patch and re-triggering the pipeline.

This capability facilitates a "human-on-the-loop" model for "DevOps", where the agent manages the routine flow of code from commit to production, alerting the human supervisor only when a critical threshold of uncertainty is reached [3,4,11,14,16–18,26]. By optimizing the feedback loop between the build system and the development environment, agents reduce the cycle time of software delivery, achieving the ultimate goal of the modern SDLC, specifically the rapid, reliable, and continuous delivery of value.

5. Quantitative and Qualitative Impact Analysis

The structural transformation of the SDLC, as detailed in the preceding sections, needs a rigorous in-depth analysis of how value, efficiency, and quality are measured in software engineering. The migration from a workflow where the human developer is the sole author to an agent-augmented architecture creates a fundamental discontinuity in traditional metrics. While the architectural framework of coding agents, characterized by ReAct [13,19–22] patterns and self-healing mechanisms [3–5,12,14], promises increased velocity, it simultaneously introduces complex variables regarding cognitive load and economic viability.

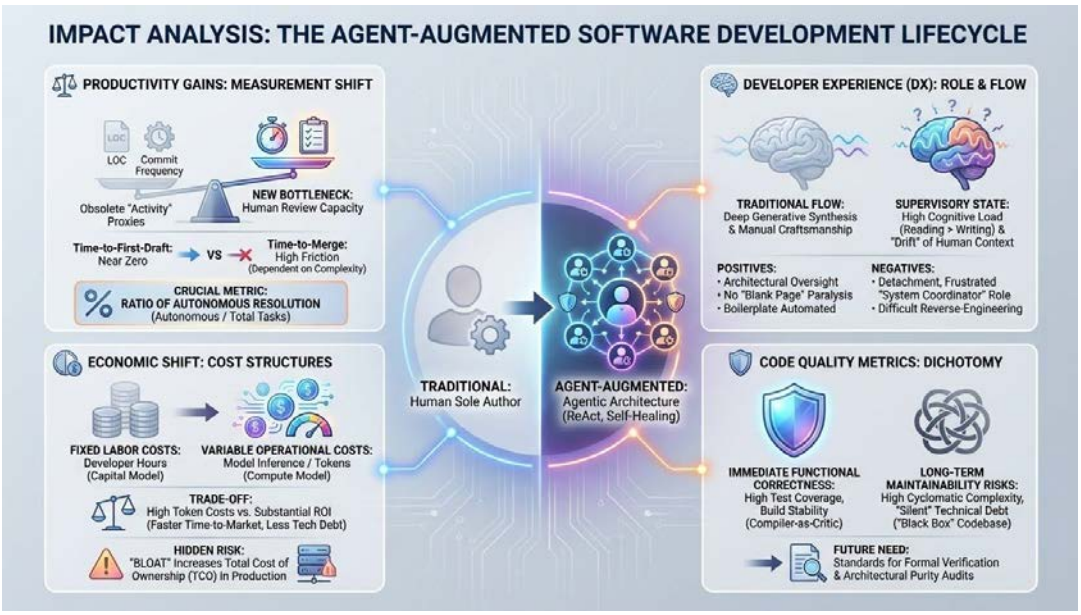


Figure 2: The Impact Analysis of the Agent-Augmented SDLC

This section performs a granular analysis of these impacts, moving beyond the superficial observation of speed in order to evaluate the deeper quantitative and qualitative shifts in productivity, developer experience, economic structures, and long-term code maintainability (Figure 2).

5.1. Productivity Gains Measurement Challenges and Empirical Data

The integration of Agentic Coding renders many traditional productivity metrics obsolete, requiring a shift toward multidimensional frameworks such as the "Satisfaction, Performance, Activity, Communication, and Efficiency" ("SPACE") model [3,16,18,26,57,58]. Historically, metrics like "Lines of Code" (LOC) or commit frequency served as proxies for developer activity. Nevertheless, in an agent-augmented model, these metrics become decoupled from actual value delivery. As established in our analysis of the implementation phase, agents can generate vast quantities of code autonomously, effectively removing human typing speed as a limiting factor. Consequently, the "Activity" dimension of the "SPACE" framework [3,16,18,26,57] may show exponential growth without a corollary increase in "Performance" or "Efficiency". If an agent generates two thousand lines of repetitive "boilerplate" code in seconds, the raw volume suggests high productivity, but if that code requires significant human auditing, the actual throughput of verified features may stagnate.

The primary bottleneck of software production has shifted from the cognitive capacity to synthesize logic into syntax to the human capacity to review and audit machine-generated logic [29,59]. Therefore, quantitative analysis must focus on "cycle time" and "change

failure rate" rather than volume [60]. The inclusion of the "Reviewer" agent in the multi-agent architecture [3,4,11,14,16–18,26] aims to mitigate this by filtering syntactic errors before they reach the human supervisor. Nevertheless, empirical observations suggest that while the "time-to-first-draft" is reduced to near zero, the "time-to-merge" remains dependent on the complexity of the generated logic [61]. True productivity gains are achieved only when the agent's output reliability exceeds the human cost of verification. If the friction of reviewing and debugging agent-generated code exceeds the effort of writing it manually, the net productivity gain turns negative. Therefore, the meaningful metric in this new paradigm is the ratio of "autonomous resolution" where the agent successfully plans, codes, and verifies a task without human intervention to the total number of tasks assigned.

5.2. Developer Experience (DX) under Cognitive Load and "Flow" State

Qualitatively, the shift to Agentic Coding fundamentally alters the psychological experience of software development, presenting a distinct trade-off between the alleviation of routine tedium and the imposition of high-level cognitive strain. The traditional state of "flow" in programming is often achieved through the deep, uninterrupted synthesis of conceptual models into code. In the agent-augmented workflow, this generative flow is frequently interrupted by the necessity of assuming the role of a "System Coordinator" or of a supervisor. The developer is no longer the author familiar with every line, which leads to a phenomenon called the "drift" of human context [4,13,14,18,27,28]. This drift creates a sense of detachment, where the engineer must constantly expend mental energy to reconstruct the logic behind the code that they did not write in order to approve it or debug it.

This transition imposes a heavy cognitive load associated with reviewing complex, machine-generated logic, which may not always align with human readability standards. Reading code is inherently more difficult than writing code, as it requires reverse-engineering the intent of the author, in this case, a synthetic entity. Nevertheless, the qualitative impact is not entirely negative. Agents significantly reduce the "blank page" situation [32,48,49] and the cognitive burden of syntax recall by handling "boilerplate" code and standard algorithms. By converting natural language directly into structured technical schemas, agents allow engineers to operate at a higher level of abstraction, focusing on architectural oversight rather than implementation details. The Developer Experience (DX) [59,62,63] therefore bifurcates, namely the satisfaction derived from manual craftsmanship diminishes, but the frustration associated with repetitive tasks and syntax errors is virtually eliminated. The challenge for the industry is to redesign the Integrated Development Environment (IDE) to support this new "supervisory" flow, potentially using visualization tools to help the human maintain the conceptual model of the system despite the erosion of the authorship context [4,13,14,18,27,28].

5.3. The Economic Shift involving Cost Reduction and Operational Overhead

The economic implications of Agentic Coding represent a complex trade-off between the fixed costs of human labor and the variable operational costs of model inference. The

paradigm shift indicates a move from a labor-intensive capital model to a compute-intensive one [30,31]. In the traditional model, the cost of development is primarily a function of developer hours. In the agent-augmented model, this is supplemented by the operational token costs required to run LLMs. Every iteration of the ReAct [13,19–22] pattern, namely every step of reasoning, planning, tool use, and self-correction consumes tokens. As agents engage in multi-step reasoning and execute self-healing test suites [3–5,12,14], the inference cost per feature scales with the complexity of the task.

Organizations must weigh these token costs against the gains in developer productivity. If an agent can autonomously refactor a legacy module in minutes, specifically a task that might have taken a human team weeks, then the return on investment is substantial, even with high inference costs. Furthermore, the economic model is impacted by the reduction in technical debt [32,52] and the acceleration of time-to-market. The capability of agents to automate requirements engineering and generate rapid prototypes allows for faster validation of business logic, potentially saving significant capital that would otherwise be spent on developing non-viable features. Nevertheless, a hidden economic risk exists in the potential for "bloat" [50,51]. If agents generate inefficient code that passes tests but consumes excessive computational resources in production, the long-term operational costs of the software itself may rise. Therefore, the economic viability of Agentic Coding depends on the cost of code generation and even more on the total cost of ownership (TCO) of the agent-generated systems, requiring a strict accounting of both the inference bill and the maintenance overhead of the resulting software artifacts.

5.4. Code Quality Metrics for Cyclomatic Complexity, Maintainability, and Technical Debt

The impact of autonomous agents on code quality metrics presents a constrast between immediate functional correctness and long-term maintainability. Agents, leveraging the "Compiler-as-Critic" feedback loop [3,4,11,14,16–18,26], are highly effective at producing code that is syntactically valid and passes unit tests. Consequently, metrics related to build stability and test coverage often improve in agent-augmented projects. Agents can autonomously generate edge cases and boundary condition tests that humans frequently overlook, leading to a more robust defense against regressions.

Nevertheless, functional validity does not guarantee structural elegance. A significant risk identified in our framework analysis is the degradation of long-term maintainability due to the "drift" of human context [4,13,14,18,27,28]. Agents may solve problems by generating convoluted logic with high cyclomatic complexity [64], provided it satisfies the immediate test constraints. Unlike human developers who often optimize for readability and future extensibility, an agent without specific architectural constraints may prioritize the path of least resistance to a green test. This can lead to an accumulation of "silent" technical debt [32,52], where the codebase becomes a "black box" of machine-generated logic that is difficult for humans to modify or refactor later. The "Reviewer" agent plays an extremely important role in enforcing "SOLID" [45–47] principles and rejecting solutions that violate established design patterns, but the risk remains that the sheer volume of generated code will overwhelm the human capacity to audit for architectural integrity. Ultimately, while defect density may decrease, the complexity density of the codebase risks increasing,

requiring new standards in formal verification in order to ensure that the software remains manageable over its lifecycle.

6. Challenges and Risks

The integration of autonomous agents into the software production line leads to a profound systemic impact on the modern SDLC, necessitating a reassessment of workflows that have historically been entirely human-centered. While the preceding analysis demonstrated how Agentic Coding can accelerate requirements engineering and revolutionize quality assurance, this transition is not without any risks. The shift from a labor-intensive capital model to a compute-intensive one introduces a new spectrum of risks that extends beyond simple syntax errors. As organizations migrate to an agent-augmented architecture where the human acts merely as a supervisor, they expose themselves to security vulnerabilities arising from the probabilistic nature of LLMs [1,2], legal ambiguities regarding intellectual property, and a fundamental degradation of the human developer's understanding of their own systems. This section of the scientific paper assesses these challenges, isolating the specific risks introduced when decision-making is relocated from syntax-level micro-management to goal-level coordination [3,4,11].

6.1. Security Vulnerabilities Arising from Hallucinations and Dependency Injection

The most immediate and extremely important risk associated with Agentic Coding arises from the inherent operational nature of the underlying models. Because LLMs [1,2] operate as advanced stochastic predictors rather than deterministic databases, they are prone to a phenomenon known as hallucination [1–4,35,36]. In the context of creative writing, a hallucination [1–4,35,36] might be a factual error, but within the strict syntax of software engineering, hallucinations often manifest as the invention of non-existent software packages or libraries. This tendency creates a severe security vector known as software supply chain attacks via dependency confusion [11,28].

When an autonomous agent is tasked with solving a complex problem, it decomposes high-level instructions into discrete tasks and attempts to import the necessary tools to execute them. If the agent's training data contains references to deprecated libraries, or if it logically infers that a library named in a specific format should exist in order to solve the immediate problem, it may hallucinate [1–4,35,36] a dependency name and insert it into the project's configuration files. Attackers can exploit this behavior by predicting common hallucinated package names and registering them on public repositories like npm or PyPI with malicious payloads [28,65,66]. Consequently, when the agent executes terminal commands to install dependencies, it inadvertently pulls malicious code into the secure development environment. Unlike a human developer who verifies the provenance of a library, the agent prioritizes the semantic probability of the package name over its verified existence.

Furthermore, the "Reviewer" agent, while designed to act as a quality gate, often struggles to identify these vulnerabilities because the hallucinated [1–4,35,36] code is syntactically correct. A line of code importing a malicious library looks identical to a legitimate import

to a reviewer focused on checking for logical validity rather than repository integrity. This creates a scenario where the automated prototyping of requirements serves as a rapid injection mechanism for vulnerabilities. The risk is compounded by the fact that agents can generate vast quantities of code autonomously, potentially burying these malicious dependencies deep within the file tree where they escape casual human audit. Therefore, the reliance on agents needs a move beyond standard code review to rigorous, automated dependency verification that is decoupled from the generative model's logic.

6.2. Intellectual Property (IP) and Licensing Concerns

The economic shift suggested by Agentic Coding involves a complex trade-off between operational token costs and developer productivity gains, but this economic model is threatened by unresolved legal questions regarding Intellectual Property (IP) [67,68]. The fundamental capability of these agents relies on their training on vast repositories of open-source code [28,65,66], which allows them to predict tokens and generate function bodies. Nevertheless, this training process ingests millions of lines of code governed by diverse licensing structures, ranging from permissive licenses like MIT and Apache to restrictive copyleft licenses like the GNU General Public License (GPL) [67,68].

A significant risk arises from the phenomenon of "regurgitation", where an agent, prompted with a specific context, reproduces snippets of training data near verbatim [28,65,66]. If an autonomous agent generates a solution that includes code derived from a GPL-licensed repository and integrates it into a proprietary commercial codebase, it effectively contaminates the licensing of the entire project. Because the agent perceives the codebase as a mutable environment [3,4,11,13–17] and operates without a legal conscience, it does not distinguish between code that is structurally useful and code that is legally compatible. This stochastic generation makes tracking the provenance of the code nearly impossible. Unlike a human developer who consciously copies code from a specific source, the agent synthesizes logic from a high-dimensional vector space, rendering the origin of any specific snippet opaque.

This opacity creates a "Black Box" liability for organizations [67]. If a company releases software generated by agents, they may inadvertently infringe on third-party IP rights, leading to litigation or the forced disclosure of proprietary source code. Furthermore, the question of ownership regarding agent-generated code remains legally ambiguous [68]. As the developer's role is redefined from syntax author to system coordinator, the threshold of human contribution required to claim copyright becomes blurred. If the human merely prompts the system and the agent decomposes the prompt and implements the logic, it is unclear whether the resulting artifact is protectable intellectual property. This uncertainty necessitates that organizations implementing agentic workflows adopt strict governance frameworks, potentially using the "Reviewer" agent to cross-reference generated code against known open-source databases to ensure license compliance before the code is merged.

6.3. The "Drift" Problem of Maintaining Human Context in Agent-Generated Codebases

While security and legal risks are external threats, the "drift" of human context represents an internal, systemic degradation of the engineering process itself [4,13,14,18,27,28] . Our analysis highlights that the increase in implementation velocity often correlates with a degradation of maintainability. As agents generate vast quantities of code autonomously, the human developer's conceptual model of the system, the "context", begins to erode. In the traditional model, the speed of development was limited by the human cognitive capacity to synthesize logic into syntax, which inherently enforced a pace that allowed for the formation of deep understanding. By removing this constraint, agents allow the codebase to grow faster than the human supervisor can comprehend it.

This phenomenon, termed the "drift" of human context [4,13,14,18,27,28], fundamentally alters the nature of ownership. As developers cease to write every line themselves, they gradually lose the deep system familiarity needed for fast debugging and sustained architectural evolution. When a complex system fails, the "Time to Recovery" is heavily dependent on the engineer's intuition regarding the system's inner workings. In an agent-augmented architecture, the code becomes a "black box" of machine-generated logic. The logic may be syntactically valid and pass all self-healing test suites [3–5,12,14], but it may also be convoluted, lacking the readability optimizations that human authors prioritize for their future selves.

The cognitive load associated with reviewing this complex, machine-generated logic is significant. Understanding code written by a synthetic entity is often more difficult than writing it from scratch, as it requires the human to reverse-engineer the agent's intent. Over time, this leads to a state where the human supervisors are afraid to modify the core logic of their applications because they do not fully understand the interdependencies that the agents have created. This results in a fragile ecosystem where the software is ostensibly robust due to automated tests, but architecturally brittle because no human holds the complete system state in their working memory [3,4,11,29]. The "Architect" agent attempts to mitigate this by maintaining high-level vision, but the ultimate responsibility for system evolution cannot be fully delegated without risking the total obsolescence of human control.

6.4. Ethical Implications of Training Data Bias and Workforce Displacement

The transformation of the software engineering field extends its impact into the ethical domain, particularly concerning the labor structures and the inherent biases within the technology. The transition to "Agentic Coding" demands a redefinition of the developer's role from syntax author to system coordinator, a shift that disproportionately affects entry-level engineers. Historically, junior developers acquired their skills by writing the repetitive "boilerplate" code that agents now automate with high efficiency. If the industry leverages agents to handle all routine implementation tasks, the apprenticeship model of computer science education is disrupted. There is a risk of creating a "missing middle" [69,70] in the workforce, where there are no pathways for juniors to gain the experience required to become the senior architects capable of supervising these agents.

Furthermore, the "drift" of human context [4,13,14,18,27,28] has ethical implications regarding accountability. If a safety-critical system fails due to code generated by an agent and approved by a human who did not fully comprehend it, the status of moral and legal responsibility is obscured. This is compounded by the bias inherent in the training data.

Agents learn from vast repositories of open-source code, which reflect the historical biases, security flaws, and bad practices of the humans who have written them. An agent does not inherently understand "quality" or "ethics", it understands statistical likelihood [3,4,7–9,16–18,26]. Consequently, it may propagate outdated or discriminatory logic structures found in legacy code, embedding them into modern applications.

The economic trade-off between operational token costs and developer productivity suggests a potential devaluation of human craftsmanship. As the barrier to creating software lowers, the market may be flooded with low-quality, derivative applications, increasing the noise-to-signal ratio in the digital ecosystem. Attaining the full potential of this technology requires a restructuring of computer science education in order to prepare the next generation for the ethical stewardship of autonomous systems besides the coding. Without these structural changes, the efficiency gains of Agentic Coding may be offset by the societal costs of job displacement [71] and the proliferation of unverified, biased algorithmic decision-making systems.

7. The Changing Role of the Human Developer

The profound systemic impact of Agentic Coding on the SDLC extends beyond the technical architecture and economic models as it fundamentally necessitates a reconstruction of the human operator's professional identity. As the industry migrates from human-centric workflows to agent-augmented architectures, the definition of "developer" is being rewritten in real-time. This transition needs, besides a change in tooling, a sociological shift that relocates the primary source of value creation from the manual synthesis of syntax to the high-level supervision of autonomous systems. The friction identified between implementation velocity and the degradation of human context suggests that the engineer of the future will function less as a craftsman of code and more as an architect of intent.

7.1. Redefining the Developer Role in the SDLC through Prompt Engineering and System Coordination

The most immediate manifestation of this role evolution is the transition from the "syntax author" to the "system coordinator". In the traditional paradigm, the developer's expertise was quantified by their fluency in specific programming languages and their ability to mentally compile complex logic structures. In an environment where autonomous agents engage in multi-step reasoning and execution, the mechanical act of typing code becomes secondary to the skill of precise specification. This elevates "Prompt Engineering" from a colloquial term to a rigorous engineering discipline within the SDLC. Unlike the stochastic interactions typical of creative chatbots, prompt engineering in an agentic context requires the formulation of unambiguous constraints, interface definitions, and functional goals that guide the ReAct [13,19–22] patterns of the model.

The human developer must now act as a coordinator, managing a suite of specialized agents, namely "Architects", "Coders", and "Reviewers", rather than executing the work

personally. This demands a capacity to decompose complex business requirements into discrete logical units that can be processed by synthetic personas without hallucination or deviation [1–4,35,36]. The developer defines the boundaries of the "sandbox" in which the agent operates, establishing the acceptance criteria that serve as the guardrails for autonomous generation. Consequently, the primary operational bottleneck shifts. It is no longer the speed at which a human can type or recall syntax that limits production, but the clarity with which they can express semantic intent to a non-human entity. This coordination role requires a complex understanding of the model's latent space and reasoning limitations, ensuring that the human-in-the-loop remains the strategic driver of a vehicle that is increasingly self-driving. The developer becomes a manager of probability, steering the stochastic nature of LLMs [1,2] toward deterministic software outcomes.

7.2. Skill Transformation in Reviewing, Debugging, and System Design

As the generative burden shifts to autonomous agents, the cognitive demands on the human developer undergo a sharp inversion. Historically, developers spent the majority of their time writing code and a minority of their time reading it. Agentic Coding inverts this ratio, placing a massive premium on the skills of reviewing, auditing, and debugging. As identified in our analysis of the "drift" of human context [4,13,14,18,27,28], the rapid generation of code by agents erodes the close connection that the author typically maintains with the codebase. The critical skill for the modern developer, therefore, is the ability to rapidly acquire context and construct a conceptual model of logic that they did not write. This moves the discipline closer to forensic analysis than creative composition.

The "Reviewer" agent may filter syntactic errors, but the human supervisor retains the ultimate responsibility for semantic validity, ensuring the code "means" what it is supposed to mean. This requires an elevated capacity for architectural oversight. The developer must be able to spot subtle logical flaws, security vulnerabilities such as hallucinated dependencies [1–4,35,36], and violations of "SOLID" [45–47] principles within complex, machine-generated logic that may not prioritize human readability. Debugging, too, transforms from correcting one's own errors to diagnosing the reasoning failures of a synthetic entity. The developer must trace the agent's "thought process" through its intermediate reasoning steps in order to understand why a specific implementation path has been chosen. This "black box" debugging requires a deep understanding of system design and integration patterns, as the individual lines of code become less significant than the interactions between modules. The competency profile of a senior engineer is consequently redefined, namely it is no longer about how many lines of code one can produce, but how effectively one can audit the structural integrity of a system built by an army of autonomous interns.

7.3. Educational Implications for the Computer Science Curricula

The redefinition of the developer's role leads to new challenges in computer science education, specifically regarding the "missing middle" [69,70] in workforce development. The traditional apprenticeship model relies on junior developers gaining skills and competence by writing the repetitive "boilerplate" code and handling routine bug fixes that

agents now automate with near-instantaneous speed [35,36]. If these foundational tasks are delegated to machines, the industry risks severing the pathway through which novices develop the deep intuition required to become senior architects. Without the struggle of writing loops and conditionals, students may fail to develop the abilities necessary to supervise the agents that write the code.

In order to mitigate this, academic curricula must undergo a structural change, moving away from syntax memorization and towards higher-order systems thinking. Computer Science education [6,7,35,36] must prioritize architectural design, formal verification methods, and the ethics of autonomous systems over routine implementation. Students must be trained in addition to coding, to evaluate the correctness of code through rigorous testing frameworks and logic proofs. The curriculum should treat "Code Review" not as a peripheral activity, but as a core competency equal to algorithm design. Furthermore, as the "drift" problem [4,13,14,18,27,28] creates fragile ecosystems where no human fully understands the system state, education must emphasize documentation standards and maintainability as primary qualities. We must cultivate a generation of engineers who are comfortable operating at high levels of abstraction, capable of managing the "black box" without losing control of the output. The goal of future education is to produce competent coordinators of autonomous intelligence, ensuring that the human element remains the governing force in an increasingly automated lifecycle.

8. Future Directions

The transition from human-centric software engineering to agent-augmented architectures marks only the emerging phase of a broader trajectory toward autonomous systems. While the current study has analyzed the immediate systemic impacts of Agentic Coding, ranging from the acceleration of requirements engineering to the risks of context drift, the rapid evolution of LLMs suggests that the underlying paradigms will continue to shift. As we look towards the horizon, three specific areas emerge as extremely important frontiers for research and industrial application, namely the progression towards fully autonomous software development organizations, the necessity of integrating formal verification to counterbalance stochastic generation, and the development of personalized agents that align with individual cognitive styles.

8.1. Towards AGI in Software Engineering through Fully Autonomous Software Development Organizations

The logical extrapolation of the current "Multi-Agent Systems" (MAS) [3,4,11,14,16–18,26] architecture is the gradual removal of the human supervisor from the immediate feedback loop, moving from a "human-in-the-loop" model to a "human-on-the-loop" or potentially "human-out-of-the-loop" configuration for defined domains. Currently, agents operate primarily as task-specific executors that require human coordination in order to manage high-level goals and resolve consensus failures. Nevertheless, as the context windows of LLMs expand and memory systems [3,4,11,29] become more robust, we anticipate the emergence of "Fully Autonomous Software Development Organizations". In

this approach, the role of the "Architect" agent will evolve from merely decomposing prompts to autonomously sensing business needs, monitoring production telemetry, and proactively initiating feature development or refactoring cycles without explicit human triggering.

This shift suggests a move towards "Artificial General Intelligence" (AGI) [3,72] within the specific vertical of software engineering. Future research must explore the dynamics of recursive self-improvement, where agents, in addition to writing their application code, also modify their own system prompts and tool definitions in order to optimize their performance. This raises profound questions regarding the "drift" of human context [4,13,14,18,27,28], namely if agents are capable of autonomously conceiving, designing, and deploying software, the resulting systems may become entirely opaque to human understanding, operating as highly efficient but impenetrable "black boxes". Consequently, the focus of software engineering research will likely shift from the mechanics of code production to the governance of autonomous fleets, establishing "Constitutional AI" frameworks that ensure these self-governing development organizations adhere to immutable safety and ethical guidelines even when operating beyond direct human oversight.

8.2. Integration with Formal Verification Methods

As observed within the study, the primary risk of Agentic Coding lies in the probabilistic nature of LLMs, which function as stochastic predictors rather than deterministic engines. This stochasticity introduces vulnerabilities such as hallucinations [1–4,35,36] and subtle logic flaws that syntactically correct code may hide. In order to mitigate these aspects, future agentic frameworks must move beyond standard unit testing and integrate directly with "Formal Verification" methods. While traditional testing validates that code works for a finite set of inputs, formal verification provides a mathematical proof that the logic adheres to a specification for all possible inputs. Historically, formal methods were considered too labor-intensive for general software development, but agents are uniquely positioned to address these problems.

Future iterations of the "Coder" and "Reviewer" agents will likely be trained besides standard programming languages on proof-carrying code and specification languages such as "Coq" [73], "Isabelle" [74,75], or "Dafny" [76]. In this workflow, an agent would simultaneously generate the mathematical proof of its correctness along with the function it codes. This integration acts as a definitive countermeasure to the "hallucination" problem [1–4,35,36], as the compiler's feedback loop would be augmented by a theorem prover that rejects any code that cannot be mathematically proven to satisfy the safety constraints. This creates a "correct-by-construction" approach where the security of the system [11,27,28,77] is guaranteed by the deterministic laws of mathematics. This shift is extremely important for the safe deployment of agents in special domains infrastructure, effectively neutralizing the risks of dependency injection and logical drift.

8.3. Personalized Agents that Learn from Individual Developer Styles

While current agents rely on vast repositories of open-source code to learn general patterns, the next frontier involves the hyper-personalization of these models to individual developers or specific organizational cultures. Currently, the generic nature of agent-generated code contributes to the "drift" of human context [4,13,14,18,27,28], as the machine produces logic that, while functional, may differ syntactically and structurally from what the human maintainer finds readable. In order to resolve this friction, future research will focus on "Small Language Models" (SLMs) [78] or "Low-Rank Adaptation" (LoRA) [79] techniques that fine-tune base models on a specific team's proprietary repositories.

These personalized agents will function as "digital twins" of the human developer, learning their specific variable naming conventions, commenting styles, and architectural preferences. By mimicking the unique cognitive fingerprint of the human supervisor, these agents can generate code that feels "native" to the author, thereby significantly reducing the cognitive load associated with reviewing machine-generated logic. This alignment preserves the "flow" state of development and helps maintain a cohesive institutional memory [3,4,11,29], as the agent adheres to the tacit knowledge and unwritten rules of the specific codebase. Nevertheless, this personalization introduces a trade-off between local efficiency and global standardization. Research must explore the tension between highly customized agents that maximize individual productivity and the need for standardized coding practices that ensure interoperability and talent mobility across the industry. Ultimately, the goal is to create agents that adapt to the human, rather than forcing the human to adapt to the synthetic output of the machine.

9. Conclusions

9.1. Summary of Key Findings

This study has systematically established that the emergence of Agentic Coding represents a transformation of the software engineering field comparable in magnitude to the advent of high-level compilers. We have determined that unlike stateless Copilots which function as stochastic predictors, autonomous agents use ReAct [13,19–22] patterns to engage in multi-step reasoning, strategic planning, and active environment interaction. The analysis has confirmed that this new approach impacts the entire SDLC, specifically by accelerating requirements engineering through automated prototyping and revolutionizing quality assurance [39–41] via self-healing test suites [3–5,12,14] where the compiler acts as an objective reviewer. Nevertheless, the integration of these autonomous systems creates a fundamental friction between increased implementation velocity and the degradation of long-term maintainability, a phenomenon identified as the "drift" of human context [4,13,14,18,27,28].

As agents generate vast quantities of code autonomously, the human developer's profound understanding of the system erodes, effectively transforming the codebase into an opaque "black box" of machine-generated logic. Furthermore, the study has highlighted extremely important risks, including security vulnerabilities arising from hallucinated [1–4,35,36] dependencies and the complex economic trade-off between operational token costs and

developer productivity gains. We have observed that while defect density regarding syntax errors may decrease due to iterative self-correction, the complexity density of the logic risks increases. Ultimately, the study has demonstrated that the primary bottleneck of software production has shifted from the cognitive capacity to synthesize logic into syntax to the capacity for architectural oversight, requiring a definitive redefinition of the developer's role from syntax author to system coordinator.

9.2. Final Recommendations for Industry Adoption

In order to successfully manage the transition to agent-augmented architectures, organizations must move beyond the passive consumption of generated code and adopt rigorous governance frameworks that address the stochastic nature of LLMs [1,2]. We consider that achieving the full potential of this technology requires the integration of formal verification methods to counterbalance the probabilistic generation of logic, ensuring that agentic outputs adhere to strict mathematical safety constraints rather than merely passing unit tests. Industry practitioners should maintain a "human-in-the-loop" or "human-on-the-loop" operational model where the developer functions as a strategic supervisor responsible for coordinating multi-agent systems [3,4,11,14,16–18,26] rather than executing manual implementation. In order to mitigate the risk of context drift [4,13,14,18,27,28], development teams must enforce comprehensive documentation standards and use specialized "Reviewer" agents to audit machine-generated logic for adherence to "SOLID" [45–47] principles and architectural integrity.

Furthermore, this technological shift demands a structural change in computer science education in order to address the potential "missing middle" [69,70] in workforce development. Curricula must evolve to prioritize systems thinking, architectural design, and ethical stewardship over routine syntax memorization, ensuring that future engineers possess the necessary abilities to supervise autonomous systems. We also recommend that organizations strictly account for the "Total Cost of Ownership", weighing the immediate velocity gains against the long-term inference costs and the maintenance overhead of complex, agent-generated ecosystems. Finally, adoption strategies must account for legal ambiguities by implementing automated dependency verification in order to prevent the accidental incorporation of hallucinated or non-compliant software packages.

Acknowledgment

"The authors would like to express their gratitude for the logistics support received from the Center of Research, Consultancy and Training in Economic Informatics and Information Technology RAU-INFORTIS of the Romanian-American University and the Center for Computational Science and Machine Intelligence of the Romanian-American University."

References

[1] Lin, T.; Wang, Y.; Liu, X.; Qiu, X. A Survey of Transformers. *AI Open* 2022, *3*, doi:10.1016/j.aiopen.2022.10.001.

[2] Tay, Y.; Dehghani, M.; Bahri, D.; Metzler, D. Efficient Transformers: A Survey. *ACM Comput Surv* 2023, *55*, doi:10.1145/3530811.

[3] Xi, Z.; Chen, W.; Guo, X.; He, W.; Ding, Y.; Hong, B.; Zhang, M.; Wang, J.; Jin, S.; Zhou, E.; et al. The Rise and Potential of Large Language Model Based Agents: A Survey. *Science China Information Sciences* 2025, *68*.

[4] Li, X.; Wang, S.; Zeng, S.; Wu, Y.; Yang, Y. A Survey on LLM-Based Multi-Agent Systems: Workflow, Infrastructure, and Challenges. *Vicinagearth* 2024, *1*, doi:10.1007/s44336-024-00009-2.

[5] Malamas, N.; Tsardoulias, E.; Panayiotou, K.; Symeonidis, A.L. Toward Efficient Vibe Coding: An LLM-Based Agent for Low-Code Software Development. *J Comput Lang* 2025, *85*, doi:10.1016/j.cola.2025.101367.

[6] Denton, M.; Chasen, A.; Fleming, G.C.; Borrego, M.; Knight, D. Agentic Actions and Agentic Perspectives Among Fellowship-Funded Engineering Doctoral Students. *Educ Sci (Basel)* 2025, *15*, doi:10.3390/educsci15101378.

[7] Addagalla, S.R.D. Engineering in the Age of AI: Leveraging Copilot for Enhanced Software Development. *International Journal of Engineering and Advanced Technology Studies* 2025, *13*, doi:10.37745/ijeats.13/vol13n12943.

[8] Xiao, Z.; He, X.; Wu, H.; Yu, B.; Guo, Y. EDA-Copilot: A RAG-Powered Intelligent Assistant for EDA Tools. *ACM Transact Des Autom Electron Syst* 2025, *30*, doi:10.1145/3715326.

[9] Döderlein, J.B.; Kouadio, N.H.; Acher, M.; Khelladi, D.E.; Combemale, B. Piloting Copilot, Codex, and StarCoder2: Hot Temperature, Cold Prompts, or Black Magic? *Journal of Systems and Software* 2025, *230*, doi:10.1016/j.jss.2025.112562.

[10] Flore, P.; Hussong, M.; Simon, P.M. Bridging the Programming Divide - Democratizing Programming Skills through GPT Assistants in Manufacturing. *ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb* 2025, *120*, doi:10.1515/zwf-2024-0130.

[11] Yan, B.; Li, K.; Xu, M.; Dong, Y.; Zhang, Y.; Ren, Z.; Cheng, X. On Protecting the Data Privacy of Large Language Models (LLMs) and LLM Agents: A Literature Review. *High-Confidence Computing* 2025, *5*.

[12] Kondus, O.; Tkachenko, O. Intellectualized Support Module of the Software Development. *Technical sciences and technologies* 2025, doi:10.25140/2411-5363-2025-2(40)-312-324.

[13] Moniruzzaman, M.; Alam, A.M. Integration of LLM and ReAct Agents for Enhanced Context Oriented Programming. In Proceedings of the 2024 27th International Conference on Computer and Information Technology, ICCIT 2024 - Proceedings; 2024.

[14] Deva, I.; Sanwal, M. An Autonomous Multi-Agent LLM Framework for Agile Software Development. *International Journal of Trend in Scientific Research and Development* 2024, *Volume-8*.

[15] Ge, S.; Sun, Y.; Cui, Y.; Wei, D. An Innovative Solution to Design Problems: Applying the Chain-of-Thought Technique to Integrate LLM-Based Agents With Concept Generation Methods. *IEEE Access* 2025, *13*, doi:10.1109/ACCESS.2024.3494054.

[16] Pan, B.; Lu, J.; Wang, K.; Zheng, L.; Wen, Z.; Feng, Y.; Zhu, M.; Chen, W. AgentCoord: Visually Exploring Coordination Strategy for LLM-Based Multi-Agent Collaboration. *Comput Graph* 2025, *132*, doi:10.1016/j.cag.2025.104338.

[17] Kalyuzhnaya, A.; Mityagin, S.; Lutsenko, E.; Getmanov, A.; Aksenkin, Y.; Fatkhiev, K.; Fedorin, K.; Nikitin, N.O.; Chichkova, N.; Vorona, V.; et al. LLM Agents for Smart City Management: Enhancing Decision Support Through Multi-Agent AI Systems. *Smart Cities* 2025, *8*, doi:10.3390/smartcities8010019.

[18] Pelluru, K. LangChain & LangGraph in Production: Architectures for Multi-Agent LLM Systems. *Journal of Data and Digital Innovation (JDDI)* 2025, *2*.

[19] Tarek RADAH ReAct-Driven SOC Agent with Integrated Detection Engineering for AI-Enhanced Autonomous Alert Handling. *Journal of Information Systems Engineering and Management* 2025, *10*, doi:10.52783/jisem.v10i53s.10967.

[20] Shaker Mahmoud, A.A.; Shishah, W.; Mistry, N.R. ReACT_OCRS: An AI-Driven Anonymous Online Reporting System Using Synergized Reasoning and Acting in Language Models. *IEEE Access* 2025, doi:10.1109/ACCESS.2025.3571526.

[21] Yuvzhenko, D.; Chymshyr, V.; Shymkovych, V.; Znova, K.; Nowakowski, G.; Telenyk, S. A Multimodal Retrieval-Augmented Generation System with ReAct Agent Logic for Multi-Hop Reasoning. *Information, Computing and Intelligent systems* 2025, doi:10.20535/2786-8729.6.2025.330777.

[22] Yan, X.; Yang, X.; Jin, N.; Chen, Y.; Li, J. A General AI Agent Framework for Smart Buildings Based on Large Language Models and ReAct Strategy. *Smart Construction* 2025, *2*, doi:10.55092/sc20250004.

[23] Yuksekgonul, M.; Bianchi, F.; Boen, J.; Liu, S.; Lu, P.; Huang, Z.; Guestrin, C.; Zou, J. Optimizing Generative AI by Backpropagating Language Model Feedback. *Nature* 2025, *639*, doi:10.1038/s41586-025-08661-4.

[24] Roy, D.; Zhang, X.; Bhave, R.; Bansal, C.; Las-Casas, P.; Fonseca, R.; Rajmohan, S. Exploring LLM-Based Agents for Root Cause Analysis. In Proceedings of the FSE Companion - Companion Proceedings of the 32nd ACM International Conference on the Foundations of Software Engineering; 2024.

[25] Hu, Q.; Tu, X.; Guo, C.; Zhang, S. Time-Aware ReAct Agent for Temporal Knowledge Graph Question Answering.; 2025.

[26] Jiang, C.; Yang, X. AgentsBench: A Multi-Agent LLM Simulation Framework for Legal Judgment Prediction. *Systems* 2025, *13*, doi:10.3390/systems13080641.

[27] Tang, X.; Jin, Q.; Zhu, K.; Yuan, T.; Zhang, Y.; Zhou, W.; Qu, M.; Zhao, Y.; Tang, J.; Zhang, Z.; et al. Prioritizing Safeguarding Over Autonomy: Risks of LLM Agents for Science. *Nature Communications 2025 16:1* 2024, *16*.

[28] Tang, Y.; Liu, Y.; Lan, J.; Yan, Z.; Gelenbe, E. Security of LLM-Based Agents Regarding Attacks, Defenses, and Applications: A Comprehensive Survey. *Information Fusion* 2026, *127*, doi:10.1016/j.inffus.2025.103941.

[29] Hatalis, K.; Christou, D.; Myers, J.; Jones, S.; Lambert, K.; Amos-Binks, A.; Dannenhauer, Z.; Dannenhauer, D. Memory Matters: The Need to Improve Long-Term Memory in LLM-Agents. *Proceedings of the AAAI Symposium Series* 2024, *2*, doi:10.1609/aaaiss.v2i1.27688.

[30] Korinek, A. AI Agents for Economic Research: August 2025 Update to 'Generative AI for Economic Research: Use Cases and Implications for Economists. *J Econ Lit* 2025, *61(4)*.

[31] O'Connor, A.J. *Organizing for Generative AI and the Productivity Revolution: Reshaping Organizational Roles in the Age of Artificial Intelligence*; 2024;

[32] Moreschini, S.; Arvanitou, E.M.; Kanidou, E.P.; Nikolaidis, N.; Su, R.; Ampatzoglou, A.; Chatzigeorgiou, A.; Lenarduzzi, V. The Evolution of Technical Debt from DevOps to Generative AI: A Multivocal Literature Review. *Journal of Systems and Software* 2026, *231*, doi:10.1016/j.jss.2025.112599.

[33] Li, H.; Hao, Y.; Zhai, Y.; Qian, Z. Enhancing Static Analysis for Practical Bug Detection: An LLM-Integrated Approach. *Proceedings of the ACM on Programming Languages* 2024, *8*, doi:10.1145/3649828.

[34] Gao, Z. A Review on Statistical Language and Neural Network Based Code Completion. *Applied and Computational Engineering* 2023, *22*, doi:10.54254/2755-2721/22/20231222.

[35] Pirzado, F.A.; Ahmed, A.; Mendoza-Urdiales, R.A.; Terashima-Marin, H. Navigating the Pitfalls: Analyzing the Behavior of LLMs as a Coding Assistant for Computer Science Students - A Systematic Review of the Literature. *IEEE Access* 2024, *12*, doi:10.1109/ACCESS.2024.3443621.

[36] Jošt, G.; Taneski, V.; Karakatič, S. The Impact of Large Language Models on Programming Education and Student Learning Outcomes. *Applied Sciences (Switzerland)* 2024, *14*, doi:10.3390/app14104115.

[37] Xing, F. Designing Heterogeneous LLM Agents for Financial Sentiment Analysis. *ACM Trans Manag Inf Syst* 2025, *16*, doi:10.1145/3688399.

[38] Kirshner, S.N.; Pan, Y.; Wu, J.X.; Gould, A. Talking Terms: Agent Information in LLM Supply Chain Bargaining. *Decision Sciences* 2025, doi:10.1111/deci.70010.

[39] Pareek, C.S. Accelerating Agile Quality Assurance with AI-Powered Testing Strategies. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT* 2024, *08*, doi:10.55041/ijsrem15369.

[40] Ahmed, A.; Kerr, E.; O'Malley, A. Quality Assurance and Validity of AI-Generated Single Best Answer Questions. *BMC Med Educ* 2025, *25*, doi:10.1186/s12909-025-06881-w.

[41] Ouyang, T.; MaungMaung, A.P.; Konishi, K.; Seo, Y.; Echizen, I. Stability Analysis of ChatGPT-Based Sentiment Analysis in AI Quality Assurance. *Electronics (Switzerland)* 2024, *13*, doi:10.3390/electronics13245043.

[42] Ben Hajhmida, M.; Lee, E.A. RAG and Agentic Assistant: A Combined Approach. In Proceedings of the Lecture Notes in Computer Science; 2026; Vol. 16220 LNCS.

[43] Pirnau, M.; Botezatu, M.A.; Priescu, I.; Hosszu, A.; Tabusca, A.; Coculescu, C.; Oncioiu, I. Content Analysis Using Specific Natural Language Processing Methods for Big Data. *Electronics (Switzerland)* 2024, *13*, doi:10.3390/electronics13030584.

[44] Aggarwal, V.; Kamal, O.; Japesh, A.; Jin, Z.; Schölkopf, B. DARS: Dynamic Action Re-Sampling to Enhance Coding Agent Performance by Adaptive Tree Traversal. In Proceedings of the Proceedings of the Annual Meeting of the Association for Computational Linguistics; 2025; Vol. 1.

[45] Cabral, R.; Kalinowski, M.; Baldassarre, M.T.; Villamizar, H.; Escovedo, T.; Lopes, H. Investigating the Impact of Solid Design Principles on Machine Learning Code Understanding. In Proceedings of the Proceedings - 2024 IEEE/ACM 3rd International Conference on AI Engineering - Software Engineering for AI, CAIN 2024; 2024.

[46] Ramachandrappa, N.C. SOLID Design Principles in Software Engineering. *International Journal of Computer Trends and Technology* 2024, *72*, doi:10.14445/22312803/ijctt-v72i9p104.

[47] Yanakiev, I.; Lazar, B.M.; Capiluppi, A. Applying SOLID Principles for the Refactoring of Legacy Code: An Experience Report. *Journal of Systems and Software* 2025, *220*, doi:10.1016/j.jss.2024.112254.

[48] Jay, R. *Generative AI Apps with LangChain and Python: A Project-Based Approach to Building Real-World LLM Apps*; 2024;

[49] Auffarth, B. *Generative AI with LangChain: Build Large Language Model (LLM) Apps with Python, ChatGPT, and Other LLMs*; 2023;

[50] Kim, A.G.; Muhn, M.; Nikolaev, V. V. Bloated Disclosures: Can ChatGPT Help Investors Process Information? *SSRN Electronic Journal* 2023, doi:10.2139/ssrn.4425527.

[51] Rekart, J.L.; Baker, R. OI, AI, and Research or Why OI Is the GOAT and AI Is the BLOAT. In *Designing for Human Intelligence in an Artificial Intelligence World*; 2025.

[52] Melo, A.; Fagundes, R.; Lenarduzzi, V.; Santos, W.B. Identification and Measurement of Requirements Technical Debt in Software Development: A Systematic Literature Review. *Journal of Systems and Software* 2022, *194*, doi:10.1016/j.jss.2022.111483.

[53] Vemuri, N.; Thaneeru, N.; Tatikonda, V.M. AI-Optimized DevOps for Streamlined Cloud CI/CD. *Int J Innov Sci Res Technol* 2024, *9*.

[54] Polinati, A. kumar Devops And Ai: Automating Software Delivery Pipelines For Continuous Integration And Deployment. *Nanotechnol Percept* 2024, *20*.

[55] Mohammed, A.S.; Saddi, V.R.; Gopal, S.K.; Dhanasekaran, S.; Naruka, M.S. AI-Driven Continuous Integration and Continuous Deployment in Software Engineering. In Proceedings of the 2024 2nd International Conference on Disruptive Technologies, ICDT 2024; 2024.

[56] SECURITY FOR CONTINUOUS INTEGRATION AND CONTINUOUS DEPLOYMENT PIPELINE. *International Research Journal of Modernization in Engineering Technology and Science* 2024, doi:10.56726/irjmets50676.

[57] Gonçalves, C.A.; Gonçalves, C.T. Assessment on the Effectiveness of GitHub Copilot as a Code Assistance Tool: An Empirical Study. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) ; 2025; Vol. 14969 LNAI.

[58] Forsgren, N.; Storey, M.A.; Maddila, C.; Zimmermann, T.; Houck, B.; Butler, J. The SPACE of Developer Productivity. *Commun ACM* 2021, *64*, doi:10.1145/3453928.

[59] Greiler, M.; Storey, M.A.; Noda, A. An Actionable Framework for Understanding and Improving Developer Experience. *IEEE Transactions on Software Engineering* 2023, *49*, doi:10.1109/TSE.2022.3175660.

[60] Forsgren, N.; Humble, J.; Kim, G.; Press, I.T.R. *Accelerate: The Science of Lean Software and Devops: Building and Scaling High Performing Technology Organizations*; 2018;

[61] Magnus Chukwuebuka Ahuchogu Evaluating the Impact of Generative AI on Intelligent Programming Assistance and Code Quality. *Power System Technology* 2025, *49*, doi:10.52783/pst.1668.

[62] Zacarias, R.O.; Antunes, L.C.R.; Barros, M. de O.; Santos, R.P. dos; Lago, P. Exploring Developer Experience Factors in Software Ecosystems. *Journal of Systems and Software* 2025, *230*, doi:10.1016/j.jss.2025.112549.

[63] Ghazali, M.; Hidayat, A.N.R. Enhancing the Developer Experience (DX) in Docker Supported Projects. *International Journal of Innovative Computing* 2023, *13*, doi:10.11113/ijic.v13n1.393.

[64] Kafura, D. Reflections on McCabe's Cyclomatic Complexity. *IEEE Transactions on Software Engineering* 2025, *51*, doi:10.1109/TSE.2025.3534580.

[65] Ji, S.L.; Wang, Q.Y.; Chen, A.Y.; Zhao, B. Bin; Ye, T.; Zhang, X.H.; Wu, J.Z.; Li, Y.; Yin, J.W.; Wu, Y.J. Survey on Open-Source Software Supply Chain Security. *Ruan Jian Xue Bao/Journal of Software* 2023, *34*, doi:10.13328/j.cnki.jos.006717.

[66] Ahmed, A.A. A COMPREHENSIVE REVIEW OF ADVERSARIAL ATTACKS IN MACHINE LEARNING. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT* 2024, *08*, doi:10.55041/ijsrem35239.

[67] Kahveci, Z.Ü. Attribution Problem of Generative AI: A View from US Copyright Law. *Journal of Intellectual Property Law and Practice* 2023, *18*, doi:10.1093/jiplp/jpad076.

[68] Samuelson, P. Legal Challenges to Generative AI, Part I: Questioning the Legality of Using in-Copyright Works for Training Data and Producing Outputs Derived from Copyrighted Training Data. *Commun ACM* 2023, *66*.

[69] Thomas, H.; Anner, M. Dissensus and Deadlock in the Evolution of Labour Governance: Global Supply Chains and the International Labour Organization (ILO). *Journal of Business Ethics* 2023, *184*, doi:10.1007/s10551-022-05177-z.

[70] Silva, V. The ILO and the Future of Work: The Politics of Global Labour Policy. *Glob Soc Policy* 2022, *22*, doi:10.1177/14680181211004853.

[71] Deckker, D.; Sumanasekara, S. Artificial Intelligence and the Future of Job Security: A Narrative Review of Risks, Resilience, and Policy Responses. *International Journal of Research and Innovation in Social Science* 2025, *IX*, doi:10.47772/ijriss.2025.906000333.

[72] Bennett, M.T. What Is Artificial General Intelligence? In Proceedings of the Lecture Notes in Computer Science; 2026; Vol. 16057 LNAI.

[73] Guo, D.; Yu, W. A Comprehensive Formalization of Propositional Logic in Coq: Deduction Systems, Meta-Theorems, and Automation Tactics. *Mathematics* 2023, *11*, doi:10.3390/math11112504.

[74] Lund, S.T.; Villadsen, J. On Verified Automated Reasoning in Propositional Logic: Teaching Sequent Calculus to Computer Science Students. *Vietnam Journal of Computer Science* 2024, *11*, doi:10.1142/S2196888824500064.

[75] From, A.H.; Schlichtkrull, A.; Villadsen, J. A Sequent Calculus for First-Order Logic Formalized in Isabelle/HOL. *Journal of Logic and Computation* 2023, *33*, doi:10.1093/logcom/exad013.

[76] Wang, J.; Chen, S.; Zhu, H. Verification of Scapegoat Trees Using Dafny. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); 2024; Vol. 14627 LNCS.

[77] Nakash, I.; Kour, G.; Uziel, G.; Anaby Tavor, A. Breaking ReAct Agents: Foot-in-the-Door Attack Will Get You In.; 2025.

[78] Fukuda, N.; Nozue, H.; Oishi, H. Small Language Model Agent for the Operations of Continuously Updating ICT Systems. *IEEE Access* 2025, *13*, doi:10.1109/ACCESS.2025.3544637.

[79] Mao, Y.; Ge, Y.; Fan, Y.; Xu, W.; Mi, Y.; Hu, Z.; Gao, Y. A Survey on LoRA of Large Language Models. *Front Comput Sci* 2025, *19*.

Bibliography

Addagalla, S.R.D. Engineering in the Age of AI: Leveraging Copilot for Enhanced Software Development. *International Journal of Engineering and Advanced Technology Studies* 2025, *13*, doi:10.37745/ijeats.13/vol13n12943.

Aggarwal, V.; Kamal, O.; Japesh, A.; Jin, Z.; Schölkopf, B. DARS: Dynamic Action Re-Sampling to Enhance Coding Agent Performance by Adaptive Tree Traversal. In Proceedings of the Proceedings of the Annual Meeting of the Association for Computational Linguistics; 2025; Vol. 1.

Ahmed, A.; Kerr, E.; O'Malley, A. Quality Assurance and Validity of AI-Generated Single Best Answer Questions. *BMC Med Educ* 2025, *25*, doi:10.1186/s12909-025-06881-w.

Ahmed, A.A. A COMPREHENSIVE REVIEW OF ADVERSARIAL ATTACKS IN MACHINE LEARNING. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT* 2024, *08*, doi:10.55041/ijsrem35239.

Auffarth, B. *Generative AI with LangChain: Build Large Language Model (LLM) Apps with Python, ChatGPT, and Other LLMs*; 2023;

Ben Hajhmida, M.; Lee, E.A. RAG and Agentic Assistant: A Combined Approach. In Proceedings of the Lecture Notes in Computer Science; 2026; Vol. 16220 LNCS.

Bennett, M.T. What Is Artificial General Intelligence? In Proceedings of the Lecture Notes in Computer Science; 2026; Vol. 16057 LNAI.

Cabral, R.; Kalinowski, M.; Baldassarre, M.T.; Villamizar, H.; Escovedo, T.; Lopes, H. Investigating the Impact of Solid Design Principles on Machine Learning Code Understanding. In Proceedings of the Proceedings - 2024 IEEE/ACM 3rd International Conference on AI Engineering - Software Engineering for AI, CAIN 2024; 2024.

David Odera; Martin Otieno; Jairus Ekume Ounza Security Risks in the Software Development Lifecycle: A Review. *World Journal of Advanced Engineering Technology and Sciences* 2023, *8*, doi:10.30574/wjaets.2023.8.2.0101.

Deckker, D.; Sumanasekara, S. Artificial Intelligence and the Future of Job Security: A Narrative Review of Risks, Resilience, and Policy Responses. *International Journal of Research and Innovation in Social Science* 2025, *IX*, doi:10.47772/ijriss.2025.906000333.

Denton, M.; Chasen, A.; Fleming, G.C.; Borrego, M.; Knight, D. Agentic Actions and Agentic Perspectives Among Fellowship-Funded Engineering Doctoral Students. *Educ Sci (Basel)* 2025, *15*, doi:10.3390/educsci15101378.

Deva, I.; Sanwal, M. An Autonomous Multi-Agent LLM Framework for Agile Software Development. *International Journal of Trend in Scientific Research and Development* 2024, *Volume-8*.

Diansyah, A.F.; Rahman, M.R.; Handayani, R.; Nur Cahyo, D.D.; Utami, E. Comparative Analysis of Software Development Lifecycle Methods in Software Development: A Systematic Literature Review. *International Journal of Advances in Data and Information Systems* 2023, *4*, doi:10.25008/ijadis.v4i2.1295.

Döderlein, J.B.; Kouadio, N.H.; Acher, M.; Khelladi, D.E.; Combemale, B. Piloting Copilot, Codex, and StarCoder2: Hot Temperature, Cold Prompts, or Black Magic? *Journal of Systems and Software* 2025, *230*, doi:10.1016/j.jss.2025.112562.

Flore, P.; Hussong, M.; Simon, P.M. Bridging the Programming Divide - Democratizing Programming Skills through GPT Assistants in Manufacturing. *ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb* 2025, *120*, doi:10.1515/zwf-2024-0130.

Forsgren, N.; Humble, J.; Kim, G.; Press, I.T.R. *Accelerate: The Science of Lean Software and Devops: Building and Scaling High Performing Technology Organizations*; 2018;

Forsgren, N.; Storey, M.A.; Maddila, C.; Zimmermann, T.; Houck, B.; Butler, J. The SPACE of Developer Productivity. *Commun ACM* 2021, *64*, doi:10.1145/3453928.

From, A.H.; Schlichtkrull, A.; Villadsen, J. A Sequent Calculus for First-Order Logic Formalized in Isabelle/HOL. *Journal of Logic and Computation* 2023, *33*, doi:10.1093/logcom/exad013.

Fukuda, N.; Nozue, H.; Oishi, H. Small Language Model Agent for the Operations of Continuously Updating ICT Systems. *IEEE Access* 2025, *13*, doi:10.1109/ACCESS.2025.3544637.

Gao, Z. A Review on Statistical Language and Neural Network Based Code Completion. *Applied and Computational Engineering* 2023, *22*, doi:10.54254/2755-2721/22/20231222.

Ge, S.; Sun, Y.; Cui, Y.; Wei, D. An Innovative Solution to Design Problems: Applying the Chain-of-Thought Technique to Integrate LLM-Based Agents With Concept Generation Methods. *IEEE Access* 2025, *13*, doi:10.1109/ACCESS.2024.3494054.

Ghazali, M.; Hidayat, A.N.R. Enhancing the Developer Experience (DX) in Docker Supported Projects. *International Journal of Innovative Computing* 2023, *13*, doi:10.11113/ijic.v13n1.393.

Gonçalves, C.A.; Gonçalves, C.T. Assessment on the Effectiveness of GitHub Copilot as a Code Assistance Tool: An Empirical Study. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) ; 2025; Vol. 14969 LNAI.

Greiler, M.; Storey, M.A.; Noda, A. An Actionable Framework for Understanding and Improving Developer Experience. *IEEE Transactions on Software Engineering* 2023, *49*, doi:10.1109/TSE.2022.3175660.

Guo, D.; Yu, W. A Comprehensive Formalization of Propositional Logic in Coq: Deduction Systems, Meta-Theorems, and Automation Tactics. *Mathematics* 2023, *11*, doi:10.3390/math11112504.

Hatalis, K.; Christou, D.; Myers, J.; Jones, S.; Lambert, K.; Amos-Binks, A.; Dannenhauer, Z.; Dannenhauer, D. Memory Matters: The Need to Improve Long-Term Memory in LLM-Agents. *Proceedings of the AAAI Symposium Series* 2024, *2*, doi:10.1609/aaaiss.v2i1.27688.

Hu, Q.; Tu, X.; Guo, C.; Zhang, S. Time-Aware ReAct Agent for Temporal Knowledge Graph Question Answering.; 2025.

Jay, R. *Generative AI Apps with LangChain and Python: A Project-Based Approach to Building Real-World LLM Apps*; 2024;

Ji, S.L.; Wang, Q.Y.; Chen, A.Y.; Zhao, B. Bin; Ye, T.; Zhang, X.H.; Wu, J.Z.; Li, Y.; Yin, J.W.; Wu, Y.J. Survey on Open-Source Software Supply Chain Security. *Ruan Jian Xue Bao/Journal of Software* 2023, *34*, doi:10.13328/j.cnki.jos.006717.

Jiang, C.; Yang, X. AgentsBench: A Multi-Agent LLM Simulation Framework for Legal Judgment Prediction. *Systems* 2025, *13*, doi:10.3390/systems13080641.

Jošt, G.; Taneski, V.; Karakatič, S. The Impact of Large Language Models on Programming Education and Student Learning Outcomes. *Applied Sciences (Switzerland)* 2024, *14*, doi:10.3390/app14104115.

Kafura, D. Reflections on McCabe's Cyclomatic Complexity. *IEEE Transactions on Software Engineering* 2025, *51*, doi:10.1109/TSE.2025.3534580.

Kahveci, Z.Ü. Attribution Problem of Generative AI: A View from US Copyright Law. *Journal of Intellectual Property Law and Practice* 2023, *18*, doi:10.1093/jiplp/jpad076.

Kalyuzhnaya, A.; Mityagin, S.; Lutsenko, E.; Getmanov, A.; Aksenkin, Y.; Fatkhiev, K.; Fedorin, K.; Nikitin, N.O.; Chichkova, N.; Vorona, V.; et al. LLM Agents for Smart City

Management: Enhancing Decision Support Through Multi-Agent AI Systems. *Smart Cities* 2025, *8*, doi:10.3390/smartcities8010019.

Kim, A.G.; Muhn, M.; Nikolaev, V. V. Bloated Disclosures: Can ChatGPT Help Investors Process Information? *SSRN Electronic Journal* 2023, doi:10.2139/ssrn.4425527.

Kirshner, S.N.; Pan, Y.; Wu, J.X.; Gould, A. Talking Terms: Agent Information in LLM Supply Chain Bargaining. *Decision Sciences* 2025, doi:10.1111/deci.70010.

Kondus, O.; Tkachenko, O. Intellectualized Support Module of the Software Development. *Technical sciences and technologies* 2025, doi:10.25140/2411-5363-2025-2(40)-312-324.

Korinek, A. AI Agents for Economic Research: August 2025 Update to 'Generative AI for Economic Research: Use Cases and Implications for Economists. *J Econ Lit* 2025, *61(4)*.

Li, H.; Hao, Y.; Zhai, Y.; Qian, Z. Enhancing Static Analysis for Practical Bug Detection: An LLM-Integrated Approach. *Proceedings of the ACM on Programming Languages* 2024, *8*, doi:10.1145/3649828.

Li, X.; Wang, S.; Zeng, S.; Wu, Y.; Yang, Y. A Survey on LLM-Based Multi-Agent Systems: Workflow, Infrastructure, and Challenges. *Vicinagearth* 2024, *1*, doi:10.1007/s44336-024-00009-2.

Lin, T.; Wang, Y.; Liu, X.; Qiu, X. A Survey of Transformers. *AI Open* 2022, *3*, doi:10.1016/j.aiopen.2022.10.001.

Lund, S.T.; Villadsen, J. On Verified Automated Reasoning in Propositional Logic: Teaching Sequent Calculus to Computer Science Students. *Vietnam Journal of Computer Science* 2024, *11*, doi:10.1142/S2196888824500064.

Magnus Chukwuebuka Ahuchogu Evaluating the Impact of Generative AI on Intelligent Programming Assistance and Code Quality. *Power System Technology* 2025, *49*, doi:10.52783/pst.1668.

Malamas, N.; Tsardoulias, E.; Panayiotou, K.; Symeonidis, A.L. Toward Efficient Vibe Coding: An LLM-Based Agent for Low-Code Software Development. *J Comput Lang* 2025, *85*, doi:10.1016/j.cola.2025.101367.

Mao, Y.; Ge, Y.; Fan, Y.; Xu, W.; Mi, Y.; Hu, Z.; Gao, Y. A Survey on LoRA of Large Language Models. *Front Comput Sci* 2025, *19*.

Melo, A.; Fagundes, R.; Lenarduzzi, V.; Santos, W.B. Identification and Measurement of Requirements Technical Debt in Software Development: A Systematic Literature Review. *Journal of Systems and Software* 2022, *194*, doi:10.1016/j.jss.2022.111483.

Mohammed, A.S.; Saddi, V.R.; Gopal, S.K.; Dhanasekaran, S.; Naruka, M.S. AI-Driven Continuous Integration and Continuous Deployment in Software Engineering. In

Proceedings of the 2024 2nd International Conference on Disruptive Technologies, ICDT 2024; 2024.

Moniruzzaman, M.; Alam, A.M. Integration of LLM and ReAct Agents for Enhanced Context Oriented Programming. In Proceedings of the 2024 27th International Conference on Computer and Information Technology, ICCIT 2024 - Proceedings; 2024.

Moreschini, S.; Arvanitou, E.M.; Kanidou, E.P.; Nikolaidis, N.; Su, R.; Ampatzoglou, A.; Chatzigeorgiou, A.; Lenarduzzi, V. The Evolution of Technical Debt from DevOps to Generative AI: A Multivocal Literature Review. *Journal of Systems and Software* 2026, *231*, doi:10.1016/j.jss.2025.112599.

Mumtaz, M.; Ahmad, N.; Usman Ashraf, M.; Alghamdi, A.M.; Bahaddad, A.A.; Almarhabi, K.A. Iteration Causes, Impact, and Timing in Software Development Lifecycle: An SLR. *IEEE Access* 2022, *10*.

Nakash, I.; Kour, G.; Uziel, G.; Anaby Tavor, A. Breaking ReAct Agents: Foot-in-the-Door Attack Will Get You In.; 2025.

O'Connor, A.J. *Organizing for Generative AI and the Productivity Revolution: Reshaping Organizational Roles in the Age of Artificial Intelligence*; 2024;

Ouyang, T.; MaungMaung, A.P.; Konishi, K.; Seo, Y.; Echizen, I. Stability Analysis of ChatGPT-Based Sentiment Analysis in AI Quality Assurance. *Electronics (Switzerland)* 2024, *13*, doi:10.3390/electronics13245043.

Pan, B.; Lu, J.; Wang, K.; Zheng, L.; Wen, Z.; Feng, Y.; Zhu, M.; Chen, W. AgentCoord: Visually Exploring Coordination Strategy for LLM-Based Multi-Agent Collaboration. *Comput Graph* 2025, *132*, doi:10.1016/j.cag.2025.104338.

Pareek, C.S. Accelerating Agile Quality Assurance with AI-Powered Testing Strategies. *INTERANTIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT* 2024, *08*, doi:10.55041/ijsrem15369.

Pelluru, K. LangChain & LangGraph in Production: Architectures for Multi-Agent LLM Systems. *Journal of Data and Digital Innovation (JDDI)* 2025, *2*.

Pirnau, M.; Botezatu, M.A.; Priescu, I.; Hosszu, A.; Tabusca, A.; Coculescu, C.; Oncioiu, I. Content Analysis Using Specific Natural Language Processing Methods for Big Data. *Electronics (Switzerland)* 2024, *13*, doi:10.3390/electronics13030584.

Pirzado, F.A.; Ahmed, A.; Mendoza-Urdiales, R.A.; Terashima-Marin, H. Navigating the Pitfalls: Analyzing the Behavior of LLMs as a Coding Assistant for Computer Science Students - A Systematic Review of the Literature. *IEEE Access* 2024, *12*, doi:10.1109/ACCESS.2024.3443621.

Polinati, A. kumar Devops And Ai: Automating Software Delivery Pipelines For Continuous Integration And Deployment. *Nanotechnol Percept* 2024, *20*.

Ramachandrappa, N.C. SOLID Design Principles in Software Engineering. *International Journal of Computer Trends and Technology* 2024, *72*, doi:10.14445/22312803/ijctt-v72i9p104.

Rekart, J.L.; Baker, R. OI, AI, and Research or Why OI Is the GOAT and AI Is the BLOAT. In *Designing for Human Intelligence in an Artificial Intelligence World*; 2025.

Roy, D.; Zhang, X.; Bhave, R.; Bansal, C.; Las-Casas, P.; Fonseca, R.; Rajmohan, S. Exploring LLM-Based Agents for Root Cause Analysis. In Proceedings of the FSE Companion - Companion Proceedings of the 32nd ACM International Conference on the Foundations of Software Engineering; 2024.

Samuelson, P. Legal Challenges to Generative AI, Part I: Questioning the Legality of Using in-Copyright Works for Training Data and Producing Outputs Derived from Copyrighted Training Data. *Commun ACM* 2023, *66*.

Saravanos, A.; Curinga, M.X. Simulating the Software Development Lifecycle: The Waterfall Model. *Applied System Innovation* 2023, *6*, doi:10.3390/asi6060108.

SECURITY FOR CONTINUOUS INTEGRATION AND CONTINUOUS DEPLOYMENT PIPELINE. *International Research Journal of Modernization in Engineering Technology and Science* 2024, doi:10.56726/irjmets50676.

Shaker Mahmoud, A.A.; Shishah, W.; Mistry, N.R. ReACT_OCRS: An AI-Driven Anonymous Online Reporting System Using Synergized Reasoning and Acting in Language Models. *IEEE Access* 2025, doi:10.1109/ACCESS.2025.3571526.

Silva, V. The ILO and the Future of Work: The Politics of Global Labour Policy. *Glob Soc Policy* 2022, *22*, doi:10.1177/14680181211004853.

Tang, X.; Jin, Q.; Zhu, K.; Yuan, T.; Zhang, Y.; Zhou, W.; Qu, M.; Zhao, Y.; Tang, J.; Zhang, Z.; et al. Prioritizing Safeguarding Over Autonomy: Risks of LLM Agents for Science. *Nature Communications 2025 16:1* 2024, *16*.

Tang, Y.; Liu, Y.; Lan, J.; Yan, Z.; Gelenbe, E. Security of LLM-Based Agents Regarding Attacks, Defenses, and Applications: A Comprehensive Survey. *Information Fusion* 2026, *127*, doi:10.1016/j.inffus.2025.103941.

Tarek RADAH ReAct-Driven SOC Agent with Integrated Detection Engineering for AI-Enhanced Autonomous Alert Handling. *Journal of Information Systems Engineering and Management* 2025, *10*, doi:10.52783/jisem.v10i53s.10967.

Tay, Y.; Dehghani, M.; Bahri, D.; Metzler, D. Efficient Transformers: A Survey. *ACM Comput Surv* 2023, *55*, doi:10.1145/3530811.

Thomas, H.; Anner, M. Dissensus and Deadlock in the Evolution of Labour Governance: Global Supply Chains and the International Labour Organization (ILO). *Journal of Business Ethics* 2023, *184*, doi:10.1007/s10551-022-05177-z.

Vemuri, N.; Thaneeru, N.; Tatikonda, V.M. AI-Optimized DevOps for Streamlined Cloud CI/CD. *Int J Innov Sci Res Technol* 2024, *9*.

Wang, J.; Chen, S.; Zhu, H. Verification of Scapegoat Trees Using Dafny. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); 2024; Vol. 14627 LNCS.

Wu, J.; Zhu, J.; Liu, Y. Agentic Reasoning: Reasoning LLMs with Tools for the Deep Research. *ArXiv* 2025.

Xi, Z.; Chen, W.; Guo, X.; He, W.; Ding, Y.; Hong, B.; Zhang, M.; Wang, J.; Jin, S.; Zhou, E.; et al. The Rise and Potential of Large Language Model Based Agents: A Survey. *Science China Information Sciences* 2025, *68*.

Xiao, Z.; He, X.; Wu, H.; Yu, B.; Guo, Y. EDA-Copilot: A RAG-Powered Intelligent Assistant for EDA Tools. *ACM Transact Des Autom Electron Syst* 2025, *30*, doi:10.1145/3715326.

Xing, F. Designing Heterogeneous LLM Agents for Financial Sentiment Analysis. *ACM Trans Manag Inf Syst* 2025, *16*, doi:10.1145/3688399.

Yan, B.; Li, K.; Xu, M.; Dong, Y.; Zhang, Y.; Ren, Z.; Cheng, X. On Protecting the Data Privacy of Large Language Models (LLMs) and LLM Agents: A Literature Review. *High-Confidence Computing* 2025, *5*.

Yan, X.; Yang, X.; Jin, N.; Chen, Y.; Li, J. A General AI Agent Framework for Smart Buildings Based on Large Language Models and ReAct Strategy. *Smart Construction* 2025, *2*, doi:10.55092/sc20250004.

Yanakiev, I.; Lazar, B.M.; Capiluppi, A. Applying SOLID Principles for the Refactoring of Legacy Code: An Experience Report. *Journal of Systems and Software* 2025, *220*, doi:10.1016/j.jss.2024.112254.

Yuksekgonul, M.; Bianchi, F.; Boen, J.; Liu, S.; Lu, P.; Huang, Z.; Guestrin, C.; Zou, J. Optimizing Generative AI by Backpropagating Language Model Feedback. *Nature* 2025, *639*, doi:10.1038/s41586-025-08661-4.

Yuvzhenko, D.; Chymshyr, V.; Shymkovych, V.; Znova, K.; Nowakowski, G.; Telenyk, S. A Multimodal Retrieval-Augmented Generation System with ReAct Agent Logic for Multi-Hop Reasoning. *Information, Computing and Intelligent systems* 2025, doi:10.20535/2786-8729.6.2025.330777.

Zacarias, R.O.; Antunes, L.C.R.; Barros, M. de O.; Santos, R.P. dos; Lago, P. Exploring Developer Experience Factors in Software Ecosystems. *Journal of Systems and Software* 2025, *230*, doi:10.1016/j.jss.2025.112549.

THE IMPACT OF AI-ASSISTED DEVELOPMENT ON THE PRODUCTIVITY OF SOFTWARE TEAMS

Teodora POPESCU[1]
Stefania GRECU[2]
Andreea-Georgiana GRIGOREANU[3]
Ana-Maria PERȘENEA[4]
Denisa-Florela MIRCEA[5]
Costin-Anton BOIANGIU[6]

Abstract

Now shaping routines in quiet ways, artificial intelligence enters routine coding tasks, altering how developers approach writing, reviewing, yet sustaining software across extended periods. Instead of fixating solely on technology, researchers examine links among AI-powered tools, personal views on output efficiency, confidence in automated decisions, while observing evolving patterns in team coordination inside tech teams. Data come from a field survey using standardized forms that collect scaled responses alongside open feedback, drawn from professionals varying in role, seniority, and frequency of AI tool usage. Though methods stay grounded in observation, emphasis rests on real voices rather than abstract trends. Each response adds texture to how automation weaves into daily practice, neither replacing nor leading but adjusting rhythms beneath the surface. Findings emerge not from theory alone, but from moments logged by those typing while assisted.

Guided by the SPACE model, this study looks at how people describe shifts in satisfaction, performance, task involvement, teamwork, and speed when using tools. At the same time, ideas from DORA help situate these experiences alongside known patterns in software delivery. Findings show those relying on AI coding aids often feel more productive and content, yet some note growing reliance on tool-generated advice. A quieter concern emerges thinking deeply about code may decline when responses come pre-filled. Risks around consistent results and reliance on output show up again and again. Wrapping up, attention shifts to how these tools fit carefully into what developers already do. One point stands out, human judgment needs structure, support, and defined roles where machines assist but do not decide.

[1] Assistant Team Coordinator, POLITEHNICA National University for Science and Technology of Bucharest, Romania, teodora.popescu@stud.acs.pub.ro
[2] Student, POLITEHNICA National University for Science and Technology of Bucharest, Romania, stefania.grecu@stud.acs.pub.ro
[3] Student, POLITEHNICA National University for Science and Technology of Bucharest, Romania, andreea.grigoreanu@stud.acs.pub.ro
[4] Student, POLITEHNICA National University for Science and Technology of Bucharest, Romania, ana.persenea@stud.acs.pub.ro
[5] PhD Student, POLITEHNICA National University for Science and Technology of Bucharest, Romania, denisa.mircea@stud.acs.upb.ro
[6] PhD, Professor, POLITEHNICA National University for Science and Technology of Bucharest, Romania, costin.boiangiu@cs.pub.ro, corresponding author

Keywords: Artificial intelligence in software engineering, Perceived software productivity, AI-based coding assistants, Empirical developer survey, SPACE productivity framework, Team collaboration

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

1. Introduction

As artificial intelligence becomes part of everyday programming, fundamental aspects of building software begin to shift without announcement. Instead of standing apart, tools such as GitHub Copilot, ChatGPT, or Amazon CodeWhisperer blend into thought processes, suggesting snippets, untangling messy logic, simplifying complex concepts, catching overlooked issues. Because they are there, behavior adjusts how people write evolves, checking updates follows altered patterns, updating legacy code demands somewhat less effort. A quiet transformation settles in through repeated small changes. Because of this, groups start questioning older measures of progress. Speed of delivery or volume of output matters less than before. Attention turns toward mood during work, cognitive load across hours, patterns in collaboration between team members. Studies show artificial intelligence helpers shorten time spent on routine coding jobs with clear boundaries [1], but still, output in programming work rarely boils down to just one number. Not just about lines written or tasks done fast, the SPACE framework combines five parts: satisfaction, group collaboration, work delivery, performance, and efficiency, these are mixing outcomes with human elements [2]. Seen this way, it becomes clearer to separate clear-cut stats such as error rates or new features shipped from how developers personally experience advancement. Central here is not time logged, yet perceived productivity, the feeling programmers hold about moving ahead without struggle. Numbers may appear strong, still staff can describe hurdles, and people sense tends to split from recorded performance. Choosing personal understanding instead of numbers by themselves guides the research direction here.

Although some findings highlight benefits, others complicate the narrative around AI in software creation. Automating routine tasks, like basic testing or standard code segments, appears to speed up workflows, according to broad data reviews [3]. Yet real-world company observations reveal gaps in who gains. For junior coders, results often tilt positive; their output improves more clearly when aided by tools. Senior practitioners, however, experience subtler shifts, with outcomes differing across projects and teams. Added mental load and collaboration demands also surface under closer inspection [4], [5]. Not every coder sees their pace matching actual performance data, some feel faster without speed showing in numbers, occasionally slipping behind instead. From different workplaces, software engineers share thoughts via questionnaires, forming the base of this inquiry. Guided by concepts from the SPACE framework along with observations tied to DORA findings, attention turns to how builders of systems perceive artificial intelligence shaping what they produce, quality reached, and ways collaboration unfolds. Progress seems lopsided, the routine actions spark greater impressions of forward motion when machines assist, while deep or learning-intensive efforts lag in perceived boost. Time spent checking machine-generated suggestions counts, but weighs less during straightforward chores,

growing heavier as difficulty climbs. So, confidence swells clearly for easier work, yet blurs into uncertainty once challenges grow complex.

2. Conceptual Foundations and Literature Review

Something odd lately, coding helpers are not stuck to strict rules anymore, moving beyond old tricks like filling brackets or reusing snippets. Instead of just catching typos, they now guess what you are after, nudging decisions based on context. Pattern-driven models take charge, drafting bits of logic, walking through why a choice fits, shaping early ideas. These are not robots ticking boxes, so they act closer to someone who gets your goal. Tools like GitHub Copilot toss out starting points, trim time hunting docs. Oddly enough, speed does not always rise, sometimes thoughts slow down, tangled in double-checking, adjusting, second-guessing each hint that pops up. Actual improvements rely strongly on how hard the task is, how skilled the person is, along with the flow shared between individual and tool [6].

Evidence from sector analyses and wide-ranging professional feedback shows similar patterns. Where tasks repeat often and carry little uncertainty, like standard code blocks, docs, or minor rewrites, generative AI proves useful. However, performance drops when handling intricate, large-scale software challenges, mostly because unchecked AI contributions may harm consistency or correctness [7]. Lately, research emphasizes framing "smart coding aids" around their function within workflows rather than focusing on model types alone. Seen through utility, these tools fulfill four core purposes such as aiding execution (easing writing of code), easing mental load (offering insights or options), ensuring standards (finding flaws or validating tests), and enabling teamwork (sharing context via summaries or records).

Sometimes AI helpers act like coding partners, stepping into roles like a driver or guide during pair work, though people still handle key decisions and fit pieces together. Still, teamwork involving machines differs fundamentally from person-to-person cooperation. Without genuine awareness of context, artificial agents may generate responses that seem plausible yet miss the mark entirely. Their value emerges only when inputs are well framed, plus the user actively challenges what gets proposed. Viewed via distributed cognition theory, such technologies reshape how mental load, focus, and recall distribute across both coder and algorithm [8]. Even though many teams now use AI tools, confidence in them wobbles since too much faith invites blind trust and too little triggers endless checking. Data from recent surveys capture this split, so uptake grows fast yet doubts about precision and consistency linger [9].

Still common measures like code volume or frequency of updates fail to reflect real impact, so researchers now turn to SPACE, a model tracking personal insight, work standard, advancement speed, teamwork flow, and effort economy [10]. With artificial intelligence becoming part of daily coding routines, behavior patterns start revealing mental conditions including tiredness, pressure, or contentment; these inner signals frequently align with stronger results and better health. Yet outcomes across groups differ, showing clearest benefit only where smart systems fit naturally within current practices. Delivery benchmarks such as DORA add background detail about pace and reliability, even if they do not shape the core analysis.

Even so, mistakes pop up often when code is shaped by artificial intelligence. Output gains can vanish, especially if checking and using AI results takes too much time, depending on skill level, task complexity, or familiarity with current codebases [4], [6]. When supervision fails to keep pace with rollout, trusting suggestions without question may introduce errors or open doors to risks, particularly in weakly protected areas [11]. However, studies tracking long-term issues like defects, vulnerabilities, or lasting impact remain rare. Extended usage might quietly shift thought processes: attention drops, problem-solving lags, reliance grows, all unnoticed due to limited evidence. Over time, few studies follow key skills like judging system designs or spotting errors. Success factors tend to stretch past software tools, customs within teams and daily office patterns seldom get detailed attention. Although many reviews frame AI assistants as individual supports, outcomes depend heavily on collective norms, instruction styles, feedback cycles, along with joint troubleshooting efforts. Such omissions drive scholars to watch carefully how programming teams integrate artificial intelligence while working routine shifts.

3. The Landscape of AI-assisted Development

Change moves fast, while artificial intelligence advances quickly, introducing varied tools aiding programming at different stages. In past iterations, most features relied on static guidelines to assess code layout together with rudimentary completion aids. Current setups leverage expansive language frameworks, grasping nearby details to propose, explain, or adjust snippets with sharper awareness. Rather than operating strictly as mechanical helpers, they begin resembling collaborative thinkers, expanding individual coder potential. Clearly spotting this change allows a look at actual effects: productivity gains, altered collaboration patterns, cleaner, or occasionally more tangled, code. Results rely strongly on how tools are built, their integration depth within daily work, and user differences, given uneven adoption across firms and experience levels.

3.1. Overview of leading AI coding tools and platforms

Software creation today sees growing use of artificial intelligence tools meant to help write, understand, and manage code. While powered mostly by large language models, such systems vary widely, some reach deep into workflows, others sit lightly atop them; some span broad functions, while others stay narrow. Inside coding platforms like Visual Studio Code or JetBrains products, one familiar presence appears: GitHub Copilot [12], built first on Codex [13], then advanced through GPT-like architectures. It suggests lines or blocks during typing, using nearby text, notes, and surrounding files as cues. Tasks like filling repetitive structures, drafting tests, or shifting syntax between frameworks become quicker with its aid. Research findings [1] show gains in speed when work stays routine and well-defined. Yet alongside those benefits come concerns, generated logic may fail quietly, flaws might slip past notice, risky patterns could emerge, legal status often remains uncertain. Safeguards inside systems do not ensure accurate outcomes, so developers must still take charge of any code they bring in. As ChatGPT emerged [14], work methods began leaning into back-and-forth help shaped by prompts. Through web interfaces or embedded software, engineers turn to it for spotting mistakes, fixing logic flaws, creating small code pieces, weighing architectural choices, or shaping early drafts of guides. Since it cannot reach internal project storage, its strength lies in broad, flexible questions across topics, but there are no situations demanding detailed knowledge of a specific setup. Over time,

improvements like outside data links and longer recall slowly reduce those barriers, making the tool more adaptable through gradual change.

Unlike others, Amazon CodeWhisperer [15] focuses on enterprise needs, secure coding, adherence to policies, smooth connections across tools, offering instant recommendations, warnings about flaws, tracking of software licenses inside AWS environments and common development editors. On a parallel track, Google's Codey [16] appears alongside Microsoft Copilot within Azure DevOps [17], mirrored by proprietary large-scale models, each blending smart completion features with oversight mechanisms. Still, assistance driven by artificial intelligence shows uneven results, where outcomes hinge on how people engage, how deeply systems link together, and what tasks are targeted, gradually influencing teamwork patterns, collective processes, and levels of potential risk.

3.2. Adoption trends across organizations and skill levels

Though AI tools are spreading faster in software work, how fast depends on company size, field limits, and what skills teams hold [7], [18]. Bigger companies stick to approved licenses and clear rules. Smaller groups move slower, worried about who owns output, whether data stays private, and if results behave predictably. Skill level shapes use newer coders lean into AI when handling routine blocks, also tangled APIs, or syntax-heavy jobs because quick help lightens mental effort. Still, hesitation remains, fed by doubts around correctness, consistency, and how well code will age. When entire groups align on how they apply such tools, results generally improve. However, isolated usage creeps in, weakening uniformity across projects. Communication grows tense as styles diverge without common ground. More effort goes into syncing efforts when teamwork depends on mismatched habits.

3.3. Cognitive and behavioral changes in the development process

What counts most is not faster coding, but how AI reshapes a programmer's mindset. Shifts in thinking run deeper than time saved. New patterns of problem-solving emerge quietly. Efficiency fades beside changes in approach. The real change hides in daily habits. Tools alter judgment more than pace ever could. Because these systems offer instant coding help, attention patterns change, so do methods for tackling problems and interacting with existing code. Often, routine or syntax-heavy jobs feel easier mentally. Such relief fits ideas about managing mental effort when support matches ability, performance and understanding grow [19]. Studies show novice coders benefit most, spending less energy grasping or writing code. Yet relying on AI answers without scrutiny might weaken thorough thinking, slowing mastery over time.

Unexpectedly, too much trust in automated decisions can backfire. Studies of how people work with smart machines show that leaning heavily on them tends to dull attention, making mistakes harder to catch [20]. When coding, this habit might lead programmers to miss bugs in lines that look right or come with strong certainty. Instead of deep planning, some now shape their approach around tweaking everyday-language prompts step by step. While faster idea testing emerges from this method, real thought may shift outside the mind, weakening grasp of core logic when artificial support replaces personal analysis instead of strengthening it. When AI influences code, it becomes unclear whose work is whose, this confusion grows during group reviews, complicating accountability. Because tracing roots matters more now, documentation of choices throughout development phases becomes

essential for groups. While progress unfolds, keeping clear logs helps maintain clarity over time. Since oversight grows harder, attention to detail in recording steps supports better outcomes later. As work advances, consistent notes allow smoother reviews when needed most.

3.4. Organizational readiness and cultural adaptation

Even when teams prepare thoroughly, weak adaptation systems erode their readiness. Performance numbers matter less than whether tools align smoothly with daily work [21]. Smooth blending into workflows depends on unseen structure, roles defined, rules set, learning available. Where teams already follow steady DevOps routines, or operate under reliable supervision, AI slips in without resistance [22]. Absent such groundwork, attempts lose momentum fast. Gains vanish just as quickly. What really shapes uptake isn't policy, but shared belief if trying new things carries little risk, minor missteps become lessons instead of setbacks. Progress holds when people know it's okay to stumble now and then. Yet pressure to perform perfectly pushes practice underground, into isolated fixes that never connect. Learning grows best through steady encouragement, which quietly balances excitement with thoughtfulness, a subtle guard against going too far [24]. Facing intense oversight, companies now reshape rules about content ownership and personal information handling, clarity turns essential [25]. Shifts that endure come less from devices, more from how people work together differently, so these adjustments uphold system reliability while aligning group actions.

4. Research Design and Methodology

4.1. Overall research strategy and rationale

Beginning with how groups apply artificial intelligence in coding tasks, the work draws from combined insights, scores given by users alongside personal accounts they shared. Instead of relying on lab settings or real-time monitoring, patterns emerge through statistics merged with free-text comments provided by participants. Human interaction shapes software creation because of that, methods mixing numbers and narratives fit better into diverse workplace routines. Recording every keystroke or decision made within a group seldom happens beyond academic proposals [26].

One way to see change is through the eyes of developers using AI tools every day compared to those stepping back or just starting. One path leads through pace, another through how people work together, both shape what clean code means in practice. Lived moments build patterns slowly, not loud but steady, shaped by who uses tools often, where they work, and their growing abilities. Productivity once ruled research, but now a quieter thought holds ground and measuring change needs many angles. What people do on the job grows out of overlapping actions, repeated patterns, mental demands, also quiet cues from surroundings. Since such elements combine in unpredictable ways, specialists view frameworks such as SPACE and DORA less as rigid scores, more as flexible views that show distinct features once put into practice [22].

4.2. Data collection procedures and tools

Among those surveyed, software professionals came from varied job levels and company types. Chosen because it supports broad reach without identifying participants, the digital questionnaire helped gather responses efficiently. Insights into how developers view

artificial intelligence in their work emerged clearly through this method, especially across differing workplace settings [27].

Not everyone joined, only those willing stepped forward. Teams arrived from varied corners of industry as fledgling tech ventures, established companies, growing businesses, and freelance advisors. Engineers who build systems, testers who check quality, operations experts managing deployments, all shared their views. Some had just started careers. Others brought ten or more years behind screens. Workplaces ranged from shops using artificial intelligence daily to places sticking with classic methods. Names stayed hidden and nothing tracked back to individuals. Each person learned upfront what the research aimed to explore and how long answers might take. Volunteers chose freely, knowing purpose and scope before contributing anything.

Broken into parts that match the research model, the survey covers several areas. First come details about age, job role, and work history, followed by how people use artificial intelligence tools across different stages of development. Instead of listing every option, questions explore personal views on speed and output improvements at work. Shifts in coding standards and career progress show up next, through individual impressions rather than metrics. Then comes group interaction: how colleagues react, whether they rely on machine suggestions, and how sure they feel using them. Open answers dig into concerns and changes in daily habits over time. Some items ask for fixed choices to build statistical clarity, others invite reflection for richer context. What emerges is a mix of data and stories shaped by how people took part.

4.3. Data analysis techniques and validation methods

A closer look at the data began with structured responses, their figures forming a base. Yet beyond these totals, comments added context, revealing motives tucked inside words. Because hard metrics alone could miss nuance, reflections helped fill gaps. When trends appeared in charts, stories explained why they mattered. Numbers gained meaning after pairing with moments people described. Only then did connections become visible, between what was measured and lived.

Figures stepped in for categories and review scores so standard math tools could work. How folks perceive situations shapes these results, rather than real-world facts. Focus shifted toward AI usage levels, job experience length, and where people worked when comparing clusters. A central idea stands, personal impressions guide findings, not fixed data points. At times, data followed expected patterns, making Welch's t-test suitable; when distributions tilted or involved ranks, Mann–Whitney U stepped in. For examining connections between coding frequency and work quality, Chi-square detected associations, then Cramer's V measured their strength. Trust and satisfaction levels, measured on an ordinal scale, led to choosing Spearman along with polychoric correlation methods for uncovering hidden connections [28], [29]. When sample sizes or statistical conditions didn't align, Kruskal–Wallis took the place of ANOVA to explore skill-related variations. From qualitative responses emerged repeated ideas, such as mental effort, dependence on tools, and difficulties in teamwork, noticed during initial review. These observations later connected with numerical trends through combined analytical approaches. Results gained stronger support by aligning them with SPACE and DORA models, showing steady changes in performance tied to real-world actions while reducing interpretive distortions [30].

4.4. Data sources and metrics

Despite relying on self-reported responses, this study ties its assessment of AI-supported coding practices to recognized models for output and deployment success. Because software work involves both people and systems, the chosen measures reflect not only how developers rate their own efficiency but also how they view teamwork and personal workflow impacts. Productivity here emerges through individual judgment, shaped by real project conditions and interaction patterns within teams.

Measuring productivity relied on the SPACE framework. Using this approach, survey questions got sorted into five areas. One area looked at how people felt about their work-life balance and job satisfaction. Another focused on personal ratings of performance when using AI support. How often tools appeared across different stages of building software formed a third category. Team dynamics, how coworkers communicated and worked together, made up the fourth part. Time saved each day due to automation rounded out the set.

How fast changes feel. Instead of hard data, developers shared views on how quickly features go live, this stands in for lead time. Deployment rhythm came through their sense of release pace, not system records. When systems broke, recovery duration was judged by personal experience, often shaped by AI tools helping fix issues. Code stability perceptions formed the basis for failure rates after AI involvement. No backend logs fed into these measures, every insight stems from individual viewpoints. What shows up here reflects opinion, not operational traces.

Although numbers fail to show everything, feelings of simplicity, consistency, and natural alignment emerged uniquely within each group [31]. From how people exchanged messages while building and reviewing work, hidden ways of acting came into view. Stories shared by individuals brought up attachment to owning ideas, uncertainty in assessing teammates' efforts with AI support, reliance on what machines produce without question. Because of this blend, weighing quick results against possible downsides, like higher upkeep demands, unclear responsibility lines, weaker bonds among members, became feasible. The resulting view depends less on software used, more on how people react within those settings.

5. Interpretation of Key Performance Indicators

Looking at how software teams perform, this section weaves together data drawn directly from practitioners working in the field. While examining AI's part in coding tasks, attention shifts toward how speed, teamwork, and confidence in decisions shift when tools assist developers. Instead of treating numbers alone as truth, findings pair hard statistics with personal accounts collected through interviews. Because context shapes what success means, each measure is weighed alongside real-world conditions faced by engineers daily. One insight stands clear, productivity cannot be boxed into a single score without losing meaning. Outcomes shift quietly, routine boundaries soften once workflow design meets leadership decisions, yet people stay in control. Adjustment shows up instead of full substitution, shaped by hands-on insight that numbers alone cannot capture [33].

5.1. Quantitative results: task efficiency, output quality, and review dynamics

A clearer sense of how tasks perform emerges when personal assessments of output quality mix with estimates of time cut by artificial intelligence, particularly where broad oversight fails [34]. Where regular and occasional users differ, the gap might not reflect real division, chance alone could shape it. Sorting signal from noise led researchers toward techniques that judge whether gaps likely persist past random chance. Conclusions only strengthen after uncertainty fades into background. Efficiency takes shape not in absolutes, but in measured doubt.

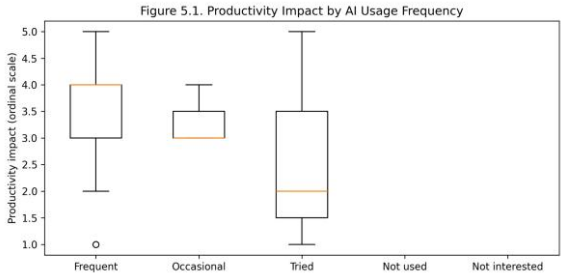


Figure 5.1 (Productivity impact by AI usage frequency) illustrates that people using AI regularly give higher median productivity ratings. On the opposite end, individuals trying the technology just once show results spread far apart, less consistency overall. Those in between, with some but limited use, fall modestly above the rest. Differences appear noticeable, though not strong enough to treat as definitive here. A Welch t-test was run on the ranked responses from 1 to 5. This analysis compared two specific cohorts as frequent AI users (n = 19) against a non-frequent group (including both occasional and trial users, n = 10). While the frequent-use group did report a higher mean productivity score (M = 3.53, SD = 1.02) than the non-frequent group (M = 3.10, SD = 1.10), the difference failed to reach statistical significance: t (17.22) = 1.02, p = 0.323. The size of the effect turned out small (d = 0.41), pointing toward only a slight link when usage happens often and better results. Because rankings were involved, researchers used a Mann–Whitney U test afterward, its outcome stayed in line with earlier data (U = 120.5, P = 0.226) yet failed to settle uncertainty.

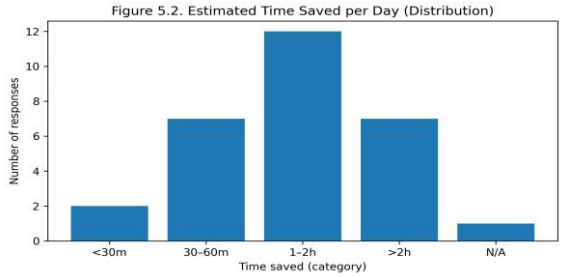


Figure 5.2 (Estimated time saved per day) indicates that most people using AI tools say they gain more than two hours each day, yet some find only thirty minutes to two hours back in their schedule. Despite differences in how much time is saved, nearly everyone notices a boost in what they get done every day, since hardly anyone says there is no real advantage, this points to changes deeper than just small tweaks. When it comes to work results,

confidence grows not only in correct code but also in how well it can be updated later and whether it holds up over time.

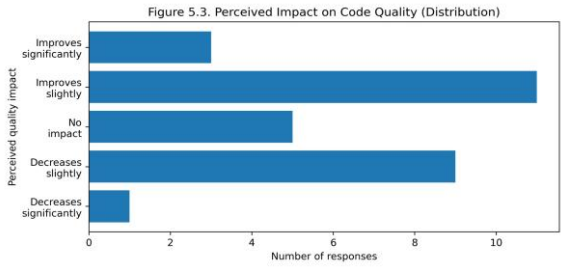


Figure 5.3 (Code quality impact distribution) indicates slight improvements in code quality for several users, a few observe worsening outcomes. Underlying problems might include overlooked bugs, excessive dependence on automation, or heavier mental demands when examining code. Such factors reveal that advantages are sometimes balanced by hidden complications.

AI Usage Level / Code Quality	**Decreases (significantly decreases)**	**Improves (significantly improves)**	**Neutral (no impact)**	**Row Total**
Frequent use	6	10	3	19
Occasional use	2	3	2	7
Tested only	2	1	0	3
Column total	10	14	5	29

Table 5.1. AI Usage Level and Perceived Code Quality (Aggregated Categories, N = 29)

Even with limited participants and scattered results, AI reliability factors split into two groups: those using it often versus those using it rarely. Shown in Table 5.1, a 2×3 layout connects frequency of use to three result types as better, stable, or poorer, making patterns easier to grasp. Because of this structure, shifts in performance become more transparent. Trends stay intact, free from skewing influences, when examined through this frame.

AI Usage Levels / Code Quality	**Decreases**	**Improves**	**Neutral**	**Row Total**
Frequent use	6	10	3	19
Non-frequent	4	4	2	10
Column total	10	14	5	29

Table 5.2. Frequent use and Non-frequent and Perceived Code Quality

AI Usage Levels / Code Quality	Decreases	Improves	Neutral
Frequent use	6.5517	9.172	3.276
Non-frequent	3.448	4.828	1.724

Table 5.3. Performance fluctuations: A comparative analysis of frequent vs. infrequent AI usage

When exploring if perspectives on code quality change alongside AI usage habits, responses fell into three categories: better, unchanged, or worse. Because of small sample size (N = 29), several cells in the initial 3×3 layout held very few cases, especially those labeled "tested only." To fix instability, researchers combined occasional users and testers into one low-use group, forming a clearer 2×3 structure. Still, statistical analysis revealed little link between regular AI use and perceived code quality; chi-square results gave $\chi^2 = 0.418$ and $p = 0.811$. Supporting that finding, Cramer's V stood at 0.12, a minimal strength of association, suggesting although individuals reported varied experiences, trends across usage types do not hold consistently within this set of respondents.

5.2. Qualitative insights: perceptions, trust, and human factors

Upon reviewing past statements, a pattern emerged where programmers rely on artificial intelligence to ease thinking and accelerate routine actions yet trust in its suggestions differs sharply among users. Some express strong faith: others remain doubtful. Speed is frequently mentioned in comments as a goal, but beneath lies tension in human-machine collaboration: depending too much on automation risks poor decisions just as much as ignoring it outright disrupts clarity [34]. That tightrope between dependence and doubt emerged as a key thread through interview remarks. Belief must be earned. Choices remain debated.

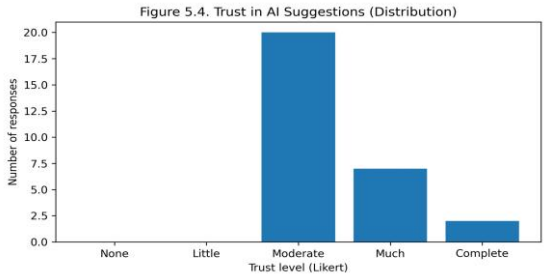
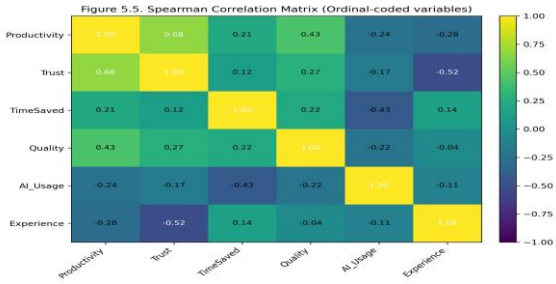


Figure 5.4 (Trust distribution) most answers fall into the middle range of trust, suggesting people adjust their faith in AI rather than fully embrace or reject it. Extreme positions, whether blind acceptance or complete doubt, appear infrequently across responses. Now seen everywhere, grasping how people perceive machine responses matters more, viewing them not as facts, yet uncertain guidance. Evidence suggests these answers often face review prior to application, shaped by individual knowledge. Depending on situation, trust changes and basic programming jobs tend draw higher reliance. Still, doubt remains regarding correctness, sparking unease around careless reasoning if suggestions are accepted too easily. This discomfort causes hesitation, though results appear solid. User comments point to constant tweaks, working systems into daily flow while keeping

authority. Movement follows movement, never pausing. Judgment waits at the final stage, unmoving.



relationships among central ideas emerge through Likert-based assessments; rank-order consistency matters more than equal spacing, making Spearman ideal despite non-linear spacing. With few participants involved, interest shifted from statistical significance toward patterns showing clear direction and real-world meaning. Throughout the visual map, a single pattern stands out, that is the greater reported trust links to improved judgments of quality, reduced effort, along with heightened perception of speed, each increasing together. Older engineers usually question AI advice more than others do. How people see dependability, their sense of possible downsides, and mental effort matter just as much as correctness. Lived practice counts heavier than claims about faster work or more results.

5.3. Comparative patterns by experience level and project type

Right away, how people experienced AI depended heavily on their skill level and the situation they were in, developers saw different outcomes [33]. For those new to coding, assistance from AI often leads to quicker progress, reducing uncertainty during early learning phases. Supportive feedback loops form when suggestions guide decisions, helping novices build confidence without getting stuck too long. Meanwhile, experienced programmers report less consistent gains, some even find the process slows them down. Gaps open when automated output demands review, interrupting rhythm developed through years of routine. Familiar patterns clash with unfamiliar prompts, creating friction rather than flow. Some groups advance more slowly than others. Yet results frequently fall short of what was hoped.

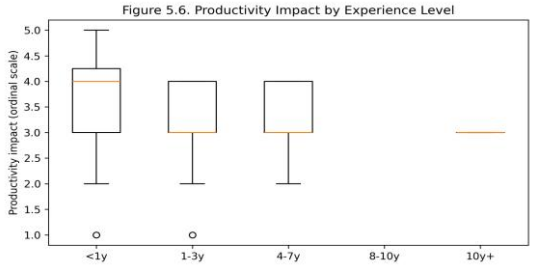


Figure 5.6 (Productivity impact by experience level) illustrates this moderating pattern, a trend I observed when synthesizing the disparate gains across career stages, where junior developers report the most substantial median productivity improvements, followed by a more modest uptick among mid-level staff. With only a few participants among the most experienced group, conclusions about veteran developers remain uncertain, yet signs point

to a leveling off. Though limited, the pattern suggests gains taper off later in their careers. Shifting demands, like tighter quality controls, drove up time spent reviewing work. That extra scrutiny came at a cost and faster progress gave way to stronger design foundations. Performance varies too much to assume consistent results across settings. The environment shapes outcomes more than experience alone.

In this analysis, the ANOVA compared three experience groups (<1 year, 1–3 years, 4–7 years), excluding the >10 years category because n = 1. Thus, $k = 3$ and $N = 28$, yielding:

$df_{(\text{between})} = 2$ and $df_{(\text{within})} = 25$, with $F(2, 25)$. Let $\bar{x} = \Sigma x_{ij} / N = 3.393$ and $SSbetween = 1.576$ and $SSwithin = 29.1$. Hence: $MSbetween = SSbetween/ dfbetween = 0.788$ and $MSwithin = SSwithin/ dfwithin = 1.164$ so that: $F = MSbetween/ MSwithin = 0.68$, $\eta^2 = 0.051$, H=1.82 and p=0.402.

Addressing the possibility of variance across career stages, I obtained $F(2, 25) = 0.68$ with a corresponding $p = 0.517$, results that preclude any claim of statistically significant differences. These figures, notably characterized by a small effect size of $\eta^2 = 0.051$, suggest that the experience groups do not diverge in a measurable way. Instead of relying solely on parametric methods, a different route emerged: applying the Kruskal–Wallis test suited for ranked outcomes. That alternative approach also found no notable separation among categories ($H = 1.82$, $p = 0.402$). Differences spread too thin when viewed as a whole, sharp calls or firm takeaways can't follow from such scattered results.

5.4. Cross-validation of quantitative and qualitative evidence

Though numbers offered some insight, they failed to show the full picture, so researchers combined methods to uncover mismatches between data and reality [32]. Validity of improvements depended on actual assistance available in relevant cases, relationships between daily routines and reported results were probed using Chi-square tests [28]. Context matters deeply in managing teams with AI, because how people think and interact often steers outcomes more than metrics suggest [33].

6. Framework for Responsible AI Integration in Software Teams

6.1. Principles for ethical and sustainable use of AI assistants

What first caught attention wasn't the system's performance, yet tiny mismatches in early outputs revealed underlying flaws. Over months, influence grew not from algorithms alone, but from shifts in team routines [20], [25], [33], altering tool adaptation gradually. From this emerged a method shaped around five ideas. At its heart sat openness and supervision, applied via clear signs when AI contributed (such as notes in commits or tags in requests), ensuring actions stayed trackable [25], and still upholding that people must answer for outcomes. A method took shape, "humans always involved unless otherwise removed", where outputs from artificial intelligence count only as preliminary sketches. From my standpoint, compromise here is not an option; code demands inspection, validation, and personal liability, especially once vulnerabilities appear or reasoning grows intricate [21], [33].

Although less visible, fairness mattered deeply, so choices could not tilt toward more experienced roles. Instead of counting hours alone, performance drew from multiple angles, how fast work finished, whether it stayed accurate, if others contributed smoothly, and even

how people felt during the process. Hidden risks needed attention too, which is why digital safety steps came next, privacy rules tightened control over information flow. Automated checks hunted for exposed secrets, while isolated systems limited exposure. Monitoring did not stop at launch and ongoing tracking ensured issues surfaced before they grew. Shifting impacts of AI mean relying on both DORA metrics and human elements from SPACE guides how I judge things. Without frequent check-ins, understanding stays shallow, figures alone miss too much. Though data helps, it cannot carry the full weight. What matters emerges only through ongoing reflection. Moments of review reveal what static reports hide. Context shapes how we see exact numbers. As choices unfold in real time, weaknesses in oversight start showing up.

6.2. Balancing automation, oversight, and human creativity

Most of the time, automation makes sense after basics are clear: when it comes to repeating actions like filling in code frames, small corrections, or standard checks, artificial intelligence works well, yet planning structure or solving intricate logic still depends on people [20, 33]. For vital parts, oversight by a person remains necessary since models often lack awareness of background details, particularly during uncertain or shifting conditions.

Few realize how quietly inspection shapes today's standards. Oversight slips in, not by choice but by need. Rather than accepting artificial intelligence outputs at face value, the process treats them merely as initial drafts. Each result faces review like human-generated work, through comparison with peers, repeated testing, sometimes close inspection of reasoning paths. Prompted by unease around unquestioning faith in fluent responses, this layer challenges assumptions that slick presentation means accuracy [20]. Used as a device to stretch thought during concept shaping, not to override decisions, I aimed to keep core human abilities intact. In the end, even when automation manages scale, control over creation stays with the engineer.

6.3. Organizational implications for Agile and DevOps practices

Because alignment matters, this framework ties AI use straight into current Agile and DevOps practices. From working alongside Agile groups, speeding up parts of development rarely cuts down time needed later for checks or merging work. So, viewing AI-written code as extra bandwidth tends to overload teams while distorting how fast progress really is. Instead, I built space for thorough verification right into sprint forecasts, making sure effort predictions cover everything from start to stable deployment, not only the first draft.

Because AI alters how teams work, old measures like delivery speed and error rates face new pressures. When moving faster, stability can slip unless safeguards stay strong. Every update shaped by artificial intelligence now moves through regular testing lanes before going live. Checks for performance and errors remain active at each stage. This keeps quality steady even when tools accelerate output [22].

Junior developers now turn to AI for support, whereas seniors spend greater time shaping system structure and overarching plans. Review methods shifted accordingly, less attention goes to detailed code inspection, more to architecture and potential risks. A mix of Agile, DORA, and SPACE measures brings clarity, revealing effort once buried in teamwork and validation tasks. What was overlooked before now shows up clearly.

6.4. Training and continuous learning strategies

Now it takes more than luck to make real progress, planning matters. Skills must grow alongside tools, shaped by design rather than chance. Writing prompts well becomes essential, since coding changes from start to finish when machines join the process. Reviewing shifts, thinking adapts, learning deepens, all affected differently. Falling short in skill while tools advance is a gap that widens fast. Progress demands matching pace, each leap met with equal learning.

Young programmers today grow both foundational abilities and keener thinking at once. Code written by automated tools offers a way to examine results alongside built-in logic, walking through functions one at a time, this often uncovers problems tucked beneath the surface. Not meant to replace insight, such technology strengthens comprehension when treated as a mirror for individual thought. Skilled programmers tend to follow another route entirely and combining human judgment with machine output matters most during tasks where smart software sharpens known abilities. Evaluating design choices or simplifying how files are structured appear here, tackling concerns such as maintenance over years and closer inspection directly rather than looking away.

Only later do we see it, growth hides in daily work, such as checking code or discussing plans once a sprint finishes. Errors surface, then become learning moments because someone looks closer. Thoughts move from one person to another like folded messages slipped beneath a doorway: unspoken yet clear. What people expect changes bit by bit, formed more by routine experience than big declarations. Over time, clarity emerges, grasp of artificial intelligence builds slowly, never in one fixed session. While operating, its shape adapts. New fragments enter via short bursts of data. Almost at once, changing documents adjust in parallel. Motion happens during use.

6.5. Risks, limitations, and contextual factors

When used beyond labs, artificial intelligence operates within limits, not because of the technology's flaws, but due to tangled workflows inside institutions. Shifts in results emerge slowly, shaped more by how teams function than by code upgrades. Hidden routines influence decisions, often overriding system capabilities. Readiness gaps dull impact, even when tools perform well on paper.

A first concern showed up fast, automation bias. Sometimes developers trust outputs simply because they look polished, though flawed underneath, inviting unseen errors or weak spots in safety [20]. Still, issues grow with broad-use models, when accuracy matters, these systems falter, lacking memory of earlier decisions or how teams operate, so support shifts toward confusion [4], [9]. Starting fast may end slow, effort piles up, outcomes lag working solo. This approach presumes zero at every stage. A single result steps into review, treated as uncertain without verification. Following alignment with recognized standards like ISO/IEC [25], progression becomes possible.

Culture influences results as powerfully as tech, though that link slips by unnoticed. Where duties are shared, movement happens, no pushing needed. Conversations nudge change, soft yet steady. A tool’s success ties closely to how people interact each day. Slow erosion of trust opens space for unseen problems to emerge. Since artificial intelligence helpers operate across wider systems, success depends on smooth fit with everyday routines instead of standalone performance. Improvement tends to come less from raw capability more from matching real-world settings. Over time, awareness grows slowly, continuous watching

matters when seeing how well these tools adjust. While tracking change, attention reveals patterns that only appear with patience.

7. Conclusions

Though speed improved, teamwork and code standards showed little improvement. Efficiency seemed higher at first, yet slowed down once reviews began. The mental effort moved elsewhere instead of disappearing, sometimes growing when checking and polishing work. Results varied widely depending on team and situation. Gains were not reliable across different settings. A closer look reveals that early gains in time frequently reappeared later once manual oversight became necessary. Shifting efficiency in one area could introduce hurdles elsewhere, particularly where responsibilities crossed paths. Identical tools were used, yet outcomes varied sharply based on experience. Automation tends to support beginners working through code, whereas seasoned professionals managing intricate setups see little gain. Such patterns highlight a core idea, effectiveness depends heavily on environment, position, and system complexity. What matters is not the tool itself but where it fits within daily work.

Still, early signs back the main idea, but just barely, when seen through careful, situation-specific scrutiny. Though interviews and polls agree tasks repeat faster thanks to tools, numbers tell a scattered story, rarely reaching firm conclusions across measures. What stands out instead is not broader efficiency, yet a shift in how mental energy gets spent. As jobs grow harder, checking work slows everything down. Oddly enough, people using these systems often report feeling quicker, even if clocks say otherwise, or worse, reveal delays hiding beneath smooth interactions.

Theoretically, this work underlines why AI-enhanced engineering should be seen through a combined social and technical lens. Merging the people-focused SPACE model with performance indicators drawn from DORA leads to one conclusion: measuring AI's effect demands context, its influence unfolds where individuals, systems, and structures meet. In real-world terms, findings suggest caution, an alert rather than applause for automation. Code produced by artificial intelligence ought to assist, not replace, human judgment. Oversight stays central, along with updated integration pipelines and learning paths built for varying skill levels. Absent these measures, gains in speed might only hide deeper flaws, a slow decline in software integrity, paired with weakened collaboration across teams.

Toward the edge of change, specialized AI agents seem bound to weave into daily work routines. Still, the real test for today's institutions lies less in processing power and more in how carefully we manage reliance on such tools. Keeping control in human hands matters, so does holding fast to sound engineering methods amid rising automated support. Studies down the line ought to follow actual outputs over time, watching how teamwork and skill-building shift across months or years. Hope stays guarded: when framed as a teammate instead of a replacement, artificial intelligence might lift output meaningfully while leaving room for people to lead.

References

[1] S. Peng, E. Kalliamvakou, P. Cihon, and M. Demirer, "The Impact of AI on Developer Productivity: Evidence from GitHub Copilot", Working Paper, Feb. 2023.

[2] B. Houck, T. Lowdermilk, C. Beyer, and S. Clarke, "The SPACE of AI: Real-World Lessons on AI's Impact on Developers", Industry Report, Aug. 2025.

[3] McKinsey & Company, "Unleashing Developer Productivity with Generative AI", McKinsey & Company Report, Jun. 2023.

[4] Z. Cui, M. Demirer, S. Jaffe, L. Musolff, S. Peng, and T. Salz, "The Effects of Generative AI on High-Skilled Work: Evidence from Three Field Experiments with Software Developers", Working Paper, Feb. 2025.

[5] J. Becker, N. Rush, B. Barnes, and D. Rein, "Measuring the Impact of Early-2025 AI on Experienced Open-Source Developer Productivity", Industry Report, Jul. 2025.

[6] P. Vaithilingam, T. Zhang, and E. L. Glassman, "Expectation vs. Experience: Evaluating the Usability of Code Generation Tools Powered by Large Language Models", in Proc. CHI Conf. Human Factors in Computing Systems Extended Abstracts, Apr. 2022.

[7] McKinsey Global Institute, "The Economic Potential of Generative AI: The Next Productivity Frontier", McKinsey Global Institute Report, Jun. 2023.

[8] E. Hutchins, _Cognition in the Wild_, MIT Press, Cambridge, MA, 1995.

[9] Stack Overflow, "Developer Survey Results 2023", Stack Overflow Inc., 2023.

[10] N. Forsgren, M.-A. Storey, C. Maddila, T. Zimmermann, B. Houck, and J. Butler, "The SPACE of Developer Productivity", Communications of the ACM, vol. 64, no. 11, pp. 62–69, Jun. 2021.

[11] H. Pearce, B. Ahmad, B. Tan, B. Dolan-Gavitt, and R. Karri, "Asleep at the Keyboard? Assessing the Security of GitHub Copilot's Code Contributions", arXiv preprint, Dec. 2021.

[12] GitHub, "GitHub Copilot: Your AI Pair Programmer", GitHub Documentation, 2024. [Online]. Available: https://github.com/features/copilot

[13] OpenAI, "Codex: An AI System for Translating Natural Language to Code", OpenAI Blog, Aug. 2021. [Online]. Available: https://openai.com/blog/openai-codex

[14] OpenAI, "API Platform Overview", OpenAI Documentation, 2024. [Online]. Available: https://platform.openai.com/docs/overview

[15] Amazon Web Services, "Amazon CodeWhisperer: AI Coding Companion", AWS Documentation, 2024. [Online]. Available: https://aws.amazon.com/codewhisperer/

[16] Google Cloud, "Codey: Generative AI for Developers", Google Cloud Documentation, 2024. [Online]. Available: https://cloud.google.com/vertex-ai/docs/generative-ai/code

[17] Microsoft, "GitHub Copilot for Business and Enterprise", Microsoft Learn, 2024. [Online]. Available: https://learn.microsoft.com/github/copilot/copilot-for-business

[18] Stack Overflow, "Developer Survey 2024: AI Tools and Developer Productivity", Industry Report, Stack Overflow, 2024. [Online]. Available: https://survey.stackoverflow.co/2024/ai

[19] J. Sweller, "Cognitive Load Theory", Psychology of Learning and Motivation, vol. 55, pp. 37–76, 2011.

[20] R. Parasuraman and V. Riley, "Humans and Automation: Use, Misuse, Disuse, Abuse", Human Factors, vol. 39, no. 2, pp. 230–253, Jun. 1997.

[21] E. L. Trist and K. W. Bamforth, "Some Social and Psychological Consequences of the Longwall Method of Coal-Getting", Human Relations, vol. 4, no. 1, pp. 3–38, 1951.

[22] N. Forsgren, J. Humble, and G. Kim, _Accelerate: The Science of Lean Software and DevOps_, IT Revolution Press, 2018.

[23] F. D. Davis, "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology", MIS Quarterly, vol. 13, no. 3, pp. 319–340, Sep. 1989.

[24] T. H. Davenport and R. Ronanki, "Artificial Intelligence for the Real World", Harvard Business Review, vol. 96, no. 1, pp. 108–116, Jan.–Feb. 2018.

[25] ISO/IEC, "ISO/IEC 23894: Information Technology – Artificial Intelligence – Risk Management", International Standard, 2023.

[26] M. A. Storey et al., "Guiding Principles for Using Mixed Methods Research in Software Engineering", IEEE Software, 2025.

[27] B. Kitchenham and S. Charters, "Guidelines for Performing Systematic Literature Reviews in Software Engineering", EBSE Technical Report EBSE-2007-01, 2007.

[28] A. Field, _Discovering Statistics Using IBM SPSS Statistics_, 4th ed., Sage, 2013, pp. 510–658.

[29] F. P. Holgado-Tello, S. Chacón-Moscoso, I. Barbero-García, and E. Vila-Abad, "Polychoric Versus Pearson Correlations in Exploratory and Confirmatory Factor Analysis of Ordinal Variables", Quality & Quantity, vol. 44, no. 1, pp. 153–166, 2010.

[30] T. D. LaToza and A. van der Hoek, "Crowdsourcing in Software Engineering: Models, Motivations, and Challenges", IEEE Software, vol. 33, no. 1, pp. 74–80, 2016.

[31] S. Amershi et al., "Guidelines for Human-AI Interaction", in Proc. CHI Conf. Human Factors in Computing Systems, 2019, pp. 1–13.

[32] J. W. Creswell, _Research Design: Qualitative, Quantitative, and Mixed Methods Approaches_, 4th ed., SAGE Publications, 2014.

[33] C. Wohlin, P. Runeson, M. Höst, M. C. Ohlsson, B. Regnell, and A. Wesslén, _Experimentation in Software Engineering_, 2nd ed., Springer Nature, 2024.

[34] J. D. Lee and K. A. See, "Trust in Automation: Designing for Appropriate Reliance", Human Factors, vol. 46, no. 1, pp. 50–80, 2004.

Bibliography

AMERSHI S., WELD D., VORVOREANU M., FOURNEY A., NUSHI B., COLLISSON P., SUH J., BENNETT P. N., INKPEN K., TEEVAN J., KIKOSKI B., HORVITZ E. – Guidelines for Human-AI Interaction – In Proc. CHI Conference on Human Factors in Computing Systems. [pp. 1–13]. 2019.

BECKER J., RUSH N., BARNES B., REIN D. – Measuring the Impact of Early-2025 AI on Experienced Open-Source Developer Productivity – Industry Report. [no pages]. July 2025.

CRESWELL J. W. – Research Design: Qualitative, Quantitative, and Mixed Methods Approaches – ISBN 978-1-4522-2609-5. SAGE Publications. [no pages]. 2014.

CUI Z., DEMIRER M., JAFFE S., MUSOLFF L., PENG S., SALZ T. – The Effects of Generative AI on High-Skilled Work: Evidence from Three Field Experiments with Software Developers – Working Paper. [no pages]. February 2025.

DAVENPORT T. H., RONANKI R. – Artificial Intelligence for the Real World – Harvard Business Review, vol. 96 no. 1. ISSN 0017-8012. [pp. 108–116]. Jan.–Feb. 2018.

DAVIS F. D. – Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology – MIS Quarterly, vol. 13 no. 3. ISSN 0276-7783. [pp. 319–340]. September 1989.

FIELD A. – Discovering Statistics Using IBM SPSS Statistics – ISBN 978-1-4462-4918-5. Sage Publications. [pp. 510–658]. 2013.

FORSGREN N., HUMBLE J., KIM G. – Accelerate: The Science of Lean Software and DevOps – ISBN 978-1-942788-33-1. IT Revolution Press. [no pages]. 2018.

FORSGREN N., STOREY M.-A., MADDILA C., ZIMMERMANN T., HOUCK B., BUTLER J. – The SPACE of Developer Productivity – Communications of the ACM, vol. 64 no. 11. ISSN 0001-0782. [pp. 62–69]. June 2021.

HOLGADO-TELLO F. P., CHACÓN-MOSCOSO S., BARBERO-GARCÍA I., VILA-ABAD E. – Polychoric Versus Pearson Correlations in Exploratory and Confirmatory Factor Analysis of Ordinal Variables – Quality & Quantity, vol. 44 no. 1. ISSN 0033-5177. [pp. 153–166]. 2010.

HUTCHINS E. – Cognition in the Wild – ISBN 978-0-262-58146-2. MIT Press, Cambridge (MA). [no pages]. 1995.

KITCHENHAM B., CHARTERS S. – Guidelines for Performing Systematic Literature Reviews in Software Engineering – EBSE Technical Report EBSE-2007-01. [no pages]. 2007.

LATOZA T. D., VAN DER HOEK A. – Crowdsourcing in Software Engineering: Models, Motivations, and Challenges – IEEE Software, vol. 33 no. 1. ISSN 0740-7459. [pp. 74–80]. 2016.

LEE J. D., SEE K. A. – Trust in Automation: Designing for Appropriate Reliance – Human Factors, vol. 46 no. 1. ISSN 0018-7208. [pp. 50–80]. 2004.

MCKINSEY & COMPANY – Unleashing Developer Productivity with Generative AI – McKinsey & Company Report. [no pages]. June 2023.

MCKINSEY GLOBAL INSTITUTE – The Economic Potential of Generative AI: The Next Productivity Frontier – McKinsey Global Institute Report. [no pages]. June 2023.

PARASURAMAN R., RILEY V. – Humans and Automation: Use, Misuse, Disuse, Abuse – Human Factors, vol. 39 no. 2. ISSN 0018-7208. [pp. 230–253]. June 1997.

PEARCE H., AHMAD B., TAN B., DOLAN-GAVITT B., KARRI R. – Asleep at the Keyboard? Assessing the Security of GitHub Copilot's Code Contributions – arXiv preprint. [no pages]. December 2021.

PENG S., KALLIAMVAKOU E., CIHON P., DEMIRER M. – The Impact of AI on Developer Productivity: Evidence from GitHub Copilot – Working Paper. [no pages]. February 2023.

STACK OVERFLOW – Developer Survey 2024: AI Tools and Developer Productivity – Industry Report, Stack Overflow. [no pages]. 2024.

STACK OVERFLOW – Developer Survey Results 2023 – Stack Overflow Inc. [no pages]. 2023.

STOREY M. A., FORTIN M., ARANDA J., ZIMMERMANN T., RICHARDSON I. – Guiding Principles for Using Mixed Methods Research in Software Engineering – IEEE Software. ISSN 0740-7459. [no pages]. 2025.

SWELLER J. – Cognitive Load Theory – Psychology of Learning and Motivation, vol. 55. ISSN 0079-7421. [pp. 37–76]. 2011.

TRIST E. L., BAMFORTH K. W. – Some Social and Psychological Consequences of the Longwall Method of Coal-Getting – Human Relations, vol. 4 no. 1. ISSN 0018-7267. [pp. 3–38]. 1951.

VAITHILINGAM P., ZHANG T., GLASSMAN E. L. – Expectation vs. Experience: Evaluating the Usability of Code Generation Tools Powered by Large Language Models – In Proc. CHI Conference on Human Factors in Computing Systems Extended Abstracts. [no pages]. April 2022.

WOHLIN C., RUNESON P., HÖST M., OHLSSON M. C., REGNELL B., WESSLÉN A. – Experimentation in Software Engineering – 2nd ed., Springer Nature. ISBN 978-3-319-91437-7. [no pages]. 2024.

Amazon Web Services – Amazon CodeWhisperer: AI Coding Companion – AWS Documentation. [online resource]. Date of last access as 16-03-2026. https://aws.amazon.com/q/developer/

GitHub – GitHub Copilot: Your AI Pair Programmer – GitHub Documentation. [online resource]. Date of last access as 16-03-2026. https://github.com/features/copilot

Google Cloud – Codey: Generative AI for Developers – Google Cloud Documentation. [online resource]. Date of last access as 16-03-2026. https://cloud.google.com/vertex-ai/docs/generative-ai/code

ISO/IEC – ISO/IEC 23894: Information Technology – Artificial Intelligence – Risk Management – International Standard. [online resource]. Date of last access as 16-03-2026.

Microsoft – GitHub Copilot for Business and Enterprise – Microsoft Learn. [online resource]. Date of last access as 16-03-2026. https://learn.microsoft.com/github/copilot/copilot-for-business

OpenAI – Codex: An AI System for Translating Natural Language to Code – OpenAI Blog. [online resource]. Date of last access as 16-03-2026. https://openai.com/index/openai-codex/

ANALYSIS OF ONLINE PURCHASING BEHAVIOR AND ONLINE SUPERMARKET USAGE AMONG YOUNG ADULTS

Takune SAKAUE[1]
Nobutaka SUZUKI[2]

Abstract
The purpose of this study is to analyze the online purchasing behavior of young adults (ages 20-29), focusing specifically on the use of online supermarkets. Overseas, online supermarkets are used by a wide range of generations, including young adults, and have a large market size. In Japan, the market size is smaller compared to overseas and the usage rate among young adults is particularly low. This study conducted quantitative research using questionnaires targeting Japanese university students. The analysis revealed that online supermarket usage among young Japanese adults is low and their use could be limited to a supplementary role in contrast to physical stores. The reasons could be that physical stores are often more accessible nearby in Japan compared to overseas and young Japanese adults perceive online supermarkets as more expensive, indicating they have psychological barriers against using them.

Keywords: Young Adults, Consumer Behavior, Online Purchasing, Online Supermarket, Questionnaire Survey

JEL Classification: D10

1. Introduction

The purpose of this study is to analyze the online purchasing behavior of young adults (ages 20-29), specifically focusing on the use of online supermarkets.

An online supermarket is defined as a "service that accepts orders via computer or mobile phone for products handled by supermarkets, such as fresh foods, processed foods, and daily necessities, and delivers them from the store" (Kawabe, 2011)[1]. In Japan, Seiyu is generally said to have been the first to start this service in 2000. The primary selling point of online supermarkets is same-day delivery, which distinguishes them significantly from

[1] Nagaoka University of Technology, Information and Management Systems Engineering, Japan, s233313@stn.nagaokaut.ac.jp
[2] Nagaoka University of Technology, Information and Management Systems Engineering, Japan, nsuzuki39@kjs.nagaokaut.ac.jp

the delivery businesses of co-ops or general online shopping sites like Rakuten and Yahoo!.

The market, which was initially small, expanded to an estimated 50 billion yen or more in 2009 (Kawabe, 2011) and reached 304 billion yen in 2023.[3] According to the 2024 Annual Statistical Survey Report on Supermarkets (National Supermarket Association, 2024)[2], a survey on the implementation rate of online supermarkets targeting 253 supermarket companies shows an increasing trend year by year: 16.9% in 2022, 20.7% in 2023, and 21.8% in 2024. Furthermore, the implementation rate of online supermarkets increases as the number of stores owned by the supermarket company increases, and companies in urban areas have higher implementation rates.

Called "Net Super" (Online Supermarket) in Japan, they are referred to as "Online Grocery" in the UK (JETRO, 2018) [3]. [4] Tesco in the UK first entered the market in 2000[5], and by the following year, sales had increased by 43% to 2.9 billion pounds, establishing its position as Europe's largest internet grocer. [6]The UK online grocery market size was estimated at approximately 11.3 billion pounds in 2017. Since major companies fully entered the market in 2012, the market has continued to grow rapidly, expanding to approximately twice the size it was in 2012 (JETRO, 2018). In the United States, 2023 sales in the eGrocery (online grocery sales) market were 95.8 billion dollars.[7]

Regarding the market size of online supermarkets mentioned above, Japan's market was 304 billion yen in 2023, whereas the UK's was approximately 11.3 billion pounds as of 2017, which is about 5.4 times that of Japan.[8] Comparing Japan and the United States in 2023, the US market is approximately 45 times larger.[9] Japan and the UK had similar entry timings for online supermarkets. Regarding the population of both countries in 2023, Japan has approximately 120 million people, while the UK has approximately 67 million, a nearly twofold difference (Statistics Bureau of Japan, 2024)[4]. Comparing the populations of Japan and the US in 2023, Japan has approximately 123.1 million people, while the US has 347.3 million, meaning the US has about three times the population of Japan. Thus, even when considering population, it can be inferred that Japan's online supermarket business is still developing compared to overseas markets.

---

[3] Fuji Keizai Group, "Press Release No. 24041" https://www.fuji-keizai.co.jp/press/detail.html?cid=24041&la=ja&la=ja (Last accessed November 24, 2025).
[4] In countries other than the UK, such as the US (Walmart, etc.), terms like "online grocery" ,"e-grocery" and "online supermarkets" are also used.
[5] SAIQOS, "Is Japan Ahead? About Online Supermarkets in the UK and US" https://www.saiqos.co.jp/marketing/2015/on-line-commerce/ (Last accessed November 24, 2025).
[6] The Guardian, "Tesco unveils £1bn profits " https://www.theguardian.com/business/2001/apr/10/tesco. (Last accessed November 24, 2025).
[7] Emi Takeda (2024) "2023 U.S. eGrocery Sales Total $95.8 Billion, Slipping 1% versus Prior Year" https://www.mercatus.com/newsroom/2023-us-egrocery-sales-total-95-8-billion/ (Last accessed October 26, 2025).
[8] According to Exchange-Rates.org (https://www.exchange-rates.org/ja/), the average exchange rate for the Japanese Yen and the British Pound in 2017 was 1 GBP = 144.26 JPY; calculations were made using this rate.
[9] According to Exchange-Rates.org (https://www.exchange-rates.org/ja/), the average exchange rate for the Japanese Yen and the US Dollar in 2023 was 1 USD = 140.53 JPY; calculations were made using this rate.

According to the 2024 Supermarket White Paper (National Supermarket Association, 2024)[5], the percentage of consumers in Japan who use online supermarkets—combining "use often," "use sometimes," and "use very occasionally"—is approximately 36%. This figure is low compared to the 57% of households in the United States that purchased groceries online in March 2025.[10] Furthermore, focusing on the utilization rate among young adults (ages 20-29): in Japan, the usage rate is highest among women in their 30s at 45%, while for those in their 20s, it is approximately 28% for men and 41% for women (National Supermarket Association, 2024). In contrast, in the UK, the demographic with the most online supermarket users is the 25–44 age group, with 62% of men and 58% of women using the service; for the 16–24 age group, 61% of men and 41% of women use the service (JETRO, 2018).

Although the current Japanese online supermarket market is growing, the market size is small compared to overseas, and the utilization rate among young adults specifically is low. Regarding this, Nakamura (2019)[6] points out that consumers currently view online supermarkets merely as a "complement" to physical stores, so usage scenarios have not expanded. Nakamura suggests that it is necessary to increase the motivation to actively use online supermarkets and to strengthen the response to young adults as a means of expanding sales channels.

However, regarding the consumer behavior of Japanese young adults, some point out that online purchasing behavior increased due to the COVID-19 pandemic (Shigeta, Sakaue, Suzuki, 2024)[7] and that this behavior has continued even after the self-restraint period (Koyama, Sakaue & Suzuki, 2025)[8].

Thus, while online supermarkets are widely popularized overseas, the utilization rate in Japan is low, contrary to the implementation rates and intentions of companies. Furthermore, while many people in their 20s use these services overseas, the rate is low in Japan. Therefore, this study focused on Japanese consumers in their 20s and conducted a quantitative study using a questionnaire, setting the research question as: "What is the current purchasing behavior of young Japanese adults regarding online shopping, specifically online supermarkets?"

This paper will review previous studies in Chapter II, explain the research overview in Chapter III, and describe the results of the quantitative analysis in Chapter IV. Chapter V will provide a discussion, and finally, Chapter VI will present the conclusion.

[10] Mercatus, "US eGrocery Sales Trends with Brick Meets Click March 2025 Insights" https://www.mercatus.com/resources/reports/us-egrocery-sales-trends-with-brick-meets-click-march-2025-insights/ (Last accessed October 26, 2025).

2. Review of Previous Studies

First, we examined previous studies of online purchasing, including online supermarkets. Jusoh and Ling (2012)[9] define online purchasing as "the process by which consumers purchase services or products over the internet." Nakano and Kondo (2019)[10], based on parameter estimation results of time-invariant independent variables, found that variables such as gender, bulk buying, time constraints, number of children, and a dummy variable for age 50–69 were significant. They found that in Japan, older women (aged 50–69) were the consumers likely to engage in online purchasing, and this trend reflected the influence of the primary household shoppers who routinely purchased daily consumer goods.

In research focusing on Japanese young adults, Shigeta et al. (2024) focused on Japanese people in their 20s and investigated how consumer behavior changed before and after the COVID-19 pandemic. The survey found that online purchasing frequency increased after the pandemic, while purchasing at physical stores tended to decrease. Koyama et al. (2025) investigated how the lives and consumer behavior of young adults changed after the relaxation of COVID-19 self-restraint. The results showed that from the self-restraint period to the post-relaxation period, online class hours decreased and the frequency of going out increased. However, there were no significant changes in the frequency of outings for shopping purposes or the time spent on online purchasing, indicating that consumer behavior did not change significantly. They cited reasons such as the self-restraint period serving as a trigger to learn about convenience, and university students becoming accustomed to the self-restraint lifestyle, which became routinized.

Regarding online purchasing overseas, Noor Afzaliza Nazira Ibrahim et al. (2023)[11] conducted a systematic review by scrutinizing 15 academic papers on the online shopping behavior of young adults.[11] The review indicated that online shopping is one of the most important trading strategies used globally and identified convenience[12] as one of the most significant influencing factors, accounting for the largest proportion of motivational factors for online shopping. Furthermore, factors influencing the decisions and behaviors of young adults in online shopping were investigated, showing that low prices have the greatest impact on their online shopping behavior.

Next, we examine previous studies focusing on online supermarkets. In research on overseas online supermarkets, Jung-Im Seo (2024)[12] investigated the online supermarket purchasing behavior of different generations in the US and their purchasing intentions during and after the COVID-19 pandemic. The study showed that Generation Y (aged 27–42) deeply understands the benefits and shopping capabilities of online supermarkets and is more likely to maintain usage than other generations. Furthermore, it pointed out that while Generation Z (aged 11–26) comprehensively understands the merits and shopping capabilities related to online supermarkets after the pandemic, they prefer to return to traditional retail stores for grocery purchases. The study considers that to acquire

[11] The reviewed papers covered consumers in the US, Asia (China, India, Vietnam, etc.), and Europe (Lithuania, Turkey, Bosnia and Herzegovina, etc.). Japanese consumers were not included.
[12] In the paper, convenience is defined as "reducing the burden of shopping and saving time."

the potential customer market of Generation Z in online supermarkets, it is essential for online grocery retailers to diversify services and strengthen marketing strategies, such as offering free delivery, discounts on shipping and handling fees, and flexible time slots.

Regarding Japanese online supermarkets, Moriuchi and Takahashi (2016)[13] surveyed repeat customers who had experience purchasing products at Japanese online supermarkets. The results showed that men accounted for 41.6% of the total, and the most common age groups were 30–39 years (18.6%), 40–49 years (39.9%), and 50–59 years (36.4%). Takahashi (2016) indicated that the average age of loyal users of the online supermarket format in Japan is 50.6 years old. Furthermore, through a comparison between online supermarket users in 2012 and format-loyal users from 2012–2016, Takahashi (2016)[14] raised issues existing in online supermarkets, such as the fact that factors influencing trust and shopping satisfaction were retail marketing factors, as well as the importance of creating shopping sites that users do not get tired of and staging enjoyment.

Regarding the use of online supermarkets by young adults, Nakamura (2019) conducted a questionnaire survey to understand how Japanese consumers use online supermarkets. Nakamura considered that consumers currently view online supermarkets merely as a "complement" to physical stores, meaning usage scenarios had not expanded, and it is necessary to increase the motivation to actively use them. Additionally, Nakamura pointed out three directions for efforts to increase consumer needs for food delivery: (1) highlighting the unique characteristics of products sold in online supermarkets, (2) enabling the receipt of the same services in online supermarkets as in physical stores, and (3) expanding the customer base (especially the younger generation, who had a synergistic relationship between the use of physical stores and online supermarkets).

As stated in Chapter I, the use of online supermarkets among young adults is high overseas but low in Japan and expanding usage among young adults has been pointed out as a challenge. While previous studies have analyzed online purchasing by young adults and the actual usage of online supermarkets by age group, there has been little focus on consumer behavior regarding online supermarket usage specifically among young adults. For the online supermarket industry, which continues to expand, acquiring young adults—who could become major future customers—can be said to be a strategic business challenge. Clarifying the actual usage by young adults has significance not only academically but also practically. Therefore, this study set the research question as "What is the current purchasing behavior of young Japanese adults regarding online shopping, specifically online supermarkets?" and conducted a quantitative study using a questionnaire.

3. Research Outline

First, the questionnaire survey of this study was based on the research of Nakamura (2019) and Koyama et al. (2025). Nakamura (2019) conducted a questionnaire survey targeting March 2018 to understand how consumers use online supermarkets. Koyama et al. (2025) conducted questionnaire and interview surveys with university students based on the research question of how their lives changed between the self-restraint period (March 2020 – March 2022) and the post-restraint period (April 2022 – November 2022) due to COVID-19.

The questionnaire content was prepared with a total of 18 questions, referencing Nakamura (2019) and Koyama et al. (2025). Questions 1 to 7 cover purchasing at physical stores and online shops, questions 8 to 13 cover the use of online supermarkets, and questions 14 to 18 are questions regarding the individual respondent (Table 1). For responses, representative answers were provided as choices, and a free-text field was provided for other answers.

This survey targeted the most recent one-month period from the time of the survey implementation (June 2024) as the target period for purchasing behavior and was conducted on 242 university students in their 20s. This target group consists of students from the same university as in Shigeta et al. (2024) and Koyama et al. (2025). The questionnaire was sent using Google Forms. The number of responses was 54 (response rate 22.3%), and excluding ambiguous responses and those with no answers, the number of valid responses was 41.

No.	Question Content	Response Format	Source
Q1	How many times a month do you shop at physical stores?	Free text	Koyama (2021)
Q2	What is your main mode of transportation when going shopping?	Multiple choice	Koyama (2021)
Q3	How many minutes does it take to drive to the place you use most often?	Free text	Koyama (2021)
Q4	How many times a month do you shop online?	Free text	Koyama (2021)
Q5	Which website do you use most for online shopping?	Multiple choice	Nakamura (2019)
Q6	What do you buy most often when shopping at physical stores?	Multiple choice	Nakamura (2019)
Q7	What do you buy most often when shopping online?	Multiple choice	Nakamura (2019)
Q8	Have you ever used an online supermarket?	Multiple choice	Nakamura (2019)
Q9	Which store's service do you use for online supermarket shopping?	Free text	Nakamura (2019)
Q10	How many times a month do you use online supermarkets?	Free text	Nakamura (2019)

Q11	What is the main reason you use online supermarkets?	Multiple choice	Nakamura (2019)
Q12	What is the main reason you do not use online supermarkets?	Multiple choice	Nakamura (2019)
Q13	Do you think you would like to use online supermarkets in the future?	Multiple choice	Koyama (2021)
Q14	Respondent's Age	Free text	
Q15	Respondent's Grade / School Year	Multiple choice	
Q16	Respondent's Gender	Multiple choice	
Q17	Does the respondent live alone?	Multiple choice	
Q18	Where does the respondent currently live?	Multiple choice	

Table 1: Questions for Quantitative Survey

4. Quantitative Research

This chapter explains the results of the data obtained from the questionnaire survey. First, survey results regarding purchasing in physical stores and online will be described, followed by survey results regarding purchasing in online supermarkets.[13]

4.1 Survey Results on Physical Stores and Online

Frequency of shopping at physical stores (times)	0	1–5	6–10	11–15	16–20	21 or more	Mean	Standard Deviation
Number of people (n)	0	8	18	2	12	1	12.46	9.66

Frequency of online shopping (times)	0	1–5	6–10	11–15	16–20	21 or more	Mean	Standard Deviation
Number of people (n)	6	35	0	0	0	0	1.56	1.26

Table 2: Purchasing Frequency in Physical Stores and Online for One Month (n=41)

Table 2 is a table showing the number of shopping trips in physical stores and online for one month. First, looking at the average number of shopping trips, physical stores were at 12.46 times compared to 1.56 times for online, showing a difference of approximately 8

[13] To make it easier for respondents to understand, the term "Net Shop" was used instead of "Online."

times. Also, while there were no respondents who used physical stores 0 times, there were 6 respondents who did not use online shopping at all. This suggests that for the subjects, physical stores are the primary means of purchasing, and there is diversity in how online shopping is used.

Next, focusing on the standard deviation, which indicates the degree of dispersion, the standard deviation for physical stores was 9.66, which is very large relative to the mean, indicating individual differences in the frequency of use. On the other hand, the standard deviation for online was small at 1.26, and the usage frequency for many people was concentrated around the mean.

Furthermore, looking at the distribution of the number of people, two peaks were seen for physical stores at "6–10 times" and "16–20 times." In contrast, for online, the distribution gradually decreased from the most common answer of "1 time," indicating that a pattern of purchasing behavior with supplementary use about once a month is most common.

Regarding the most used site for online purchasing, Amazon had the highest result at a rate of 30%, indicating a trend that many consumers use Amazon. Other sites included Yahoo! Auctions and Rakuten Ichiba.

Regarding the items most frequently purchased in physical stores and online, food, beverages, and alcohol accounted for 95% of physical stores purchases. On the other hand, computers and peripherals accounted for the largest proportion of online purchases at 17%. As for the items purchased, only three types were purchased in physical stores: food/beverages/alcohol, home & kitchen, and books/comics/magazines. However, online, a total of 11 types of products were purchased, including fashion and home appliances/cameras/AV equipment. This survey showed that young adults tend to purchase mainly food products in physical stores, while purchasing a wide variety of other items online.

4.2 Survey Results on Online Supermarkets

Regarding experience with online supermarkets, 6 out of 41 students (14.6%) answered that they had experience using them. The monthly usage frequency for the 6 users was either 0, 1, or 2 times. The services used were diverse, including Amazon (Online Supermarket), Aeon, Ito-Yokado, and community-based supermarkets, and no concentration on specific services was seen.

The 6 online supermarket users also shopped at physical stores. Since it is conceivable that online supermarket users utilize physical stores with similar frequency to non-users, a hypothesis was set that "there is no difference in the number of shopping trips at physical stores between online supermarket users and non-users," and a two-tailed t-test was performed. As a result, the difference in the average monthly shopping trips at physical stores between online supermarket users and non-users was 0.04 times, the t-value was

0.01, and the two-sided p-value was 0.99, supporting the hypothesis. In other words, it was suggested that online supermarket users shop at physical stores in the same way as non-users and use online supermarkets as needed.

Next, regarding reasons for using and not using online supermarkets, the main reasons for use cited by experienced users centered on voices evaluating the convenience provided by online supermarkets, such as "difficulty going out," "saving time," and "rich product assortment." On the other hand, the biggest reason cited by the non-user group for not using it was "because there is a physical store nearby (34%)," followed by "prices are high (26%)." Other reasons included "trouble of receiving" and "complexity of usage methods."

	Will use in the future	Probably will use in the future	Can't say / Undecided	Probably will not use in the future	Will not use in the future
Online supermarket users	3 (50.0%)	1 (16.7%)	1 (16.7%)	1 (16.7%)	0
Non-users of online supermarkets	0	6 (17.1%)	6 (17.1%)	7 (20.0%)	16 (45.7%)

Table 3: Future Intentions by Online Supermarket Usage Experience (n=41)

Regarding future intentions categorized by online supermarket usage experience, as shown in Table 3, the results were polarized depending on the presence or absence of usage experience. Specifically, responses from the user group skewed heavily toward positive opinions, with "Will use in the future" accounting for half (50.0%) and reaching approximately 67% when combined with "Will somewhat use in the future." In contrast, in the non-user group, responses were concentrated on negative opinions, with "Will not use in the future" accounting for nearly half (45.7%) and approximately 66% showing a negative view when including "Will somewhat not use in the future."

5. Discussion

First, the results of this survey suggested that the purchasing behavior of young Japanese adults remains centered on physical stores, with online usage, including online supermarkets, remaining limited and playing a complementary role. Second, although the use of online supermarkets by young Japanese adults is not very common, it was

suggested that the presence or absence of usage experience is a factor that polarizes future usage intentions. This chapter discusses what these results mean.

First is the diversity of purchasing behavior among young Japanese adults. The fact that the standard deviation for the frequency of physical store use was large (SD=9.66) is thought to reflect that the lifestyles of young adults are not uniform. The two purchasing styles shown in the results—"those who buy in bulk 1–2 times a week" and "those who buy frequently in small amounts"—are thought to be due to diversity in behavior arising from differences in life rhythms and values.

Second, the results of this survey suggested that for young Japanese adults, online supermarkets, like general online purchasing, are positioned as a complementary means to physical stores. Comparing the difference in the average number of shopping trips at physical stores between online supermarket users and non-users showed that the use of online supermarkets does not affect the frequency of physical store use. This result is consistent with Nakamura's (2019) point that users do not substitute physical stores with Japanese online supermarkets but continue to purchase at physical stores while using online supermarkets as needed. Furthermore, when compared with the finding by Nakano and Kondo (2019) that older women drive online purchasing of daily consumer goods in Japan, it is possible that a generational usage gap exists where young adults use online purchasing (including online supermarkets) as a complement, while older generations utilize it more actively.

Third, this survey clarified the nature of the barriers to the diffusion of online supermarkets in Japan through comparison with young adults overseas. In their review of online purchasing motivations among young adults overseas, Noor Afzaliza Nazira Ibrahim et al. (2023) analyzed that "convenience" and "low prices" are the two major factors promoting use. In contrast, the biggest reasons cited by non-users of online supermarkets in this survey were "having a physical store nearby," followed by "high prices." It is possible that young Japanese adults do not feel burdened by shopping at physical stores and are not satisfied with additional costs such as delivery fees or product prices of online supermarkets. This situation differs from overseas markets, and a more detailed analysis of delivery areas and fees for Japanese online supermarkets is necessary. Furthermore, the result of this survey that the presence or absence of usage experience polarizes future intentions may be grasped as a generation-specific challenge that transcends national borders, when considering the study by Jung-Im Seo (2024) analyzing Generation Z in the US.

The above content provides important suggestions for Japanese online supermarket operators targeting young adults. The first is the acquisition of non-users. Since the biggest reasons non-users in this survey cited for not using online supermarkets were "having a physical store nearby" and "high prices," simply appealing to convenience is considered insufficient. It is thought necessary to present values such as online-only discounts, price advantages through subscription models, and "saving shopping time" in

busy student lives, thereby overturning the perception of the physical and economic superiority of physical stores.

The second is the response to the polarization of evaluation due to usage experience. Since the presence or absence of online supermarket usage experience among the survey subjects determined future intentions in opposite directions, it is conceivable that for young Japanese adults, while value is easily realized once used, strong psychological barriers exist before use. Providing trials that appeal with first-time limited discounts or simple operability to fill this gap and lower the hurdle to use is considered effective in acquiring the non-user demographic of online supermarkets.

However, since this study was limited to Japanese university students as subjects, and the sample size was limited to 41, there is a limit to generalization. In the future, we desire to further elucidate what has been suggested here by conducting additional surveys. Also, since this study is an analysis limited to the consumer's perspective, challenges remain in making practical proposals. Considering that strategic approaches may not be realistic without taking into account the operational realities of the operator side, such as logistics costs, profitability, and securing personnel for online supermarkets, we believe it is necessary to conduct interview surveys or case studies with operators.

6. Conclusion

In countries such as the United States and the UK, the market size of online supermarkets is larger than in Japan, and online supermarkets are actively used regardless of age, including by young adults. On the other hand, in Japan, contrary to the implementation rates and intentions of supermarket companies, the market size of online supermarkets and the percentage of consumers using them are small, with the utilization rate among young adults (ages 20-29) being particularly low. Therefore, this study set the research question as "What is the current purchasing behavior of young Japanese adults regarding online shopping, specifically online supermarkets?" and analyzed the actual situation through a questionnaire survey targeting Japanese university students (ages 20-29) to elucidate this question.

The analysis results of this study showed that the targeted young Japanese adults clearly differentiate their usage, mainly purchasing essential food items at physical stores while purchasing diverse items with high hobby or specialized interest online. Regarding online supermarkets, which were the focus of the study, the utilization rate among young Japanese adults is low, and the results indicate that their use of online services continues to serve a role that is complementary to physical stores. This result was consistent with the findings of Nakamura (2019).

The discussion of this study suggested that two major challenges may exist as reasons why the use of online supermarkets by young Japanese adults has not progressed compared to overseas. The first point is that while "convenience" and "low prices" are the two major factors promoting the use of online purchasing (including online supermarkets) among young adults overseas (Noor Afzaliza Nazira Ibrahim et al., 2023), for young Japanese adults, the physical convenience of "having a physical store nearby" and the perception that "prices are high" act as barriers to using online supermarkets. The second point is that future usage intentions are polarized depending on the presence or absence of online supermarket usage experience. Regarding online supermarkets, it is conceivable that for young Japanese adults, value is easily realized once used, but strong psychological barriers exist before use. This suggests the existence of psychological barriers before use, which is consistent with the trend of American Generation Z (Jung-Im Seo, 2024).

In this study, two strategic approaches were presented to address these challenges. One is "acquisition of non-users" through online-only discounts and subscription models to overturn the barriers of "price" and "convenience." The other is to provide trials with first-time limited discounts and simple operability to eliminate the psychological barriers of appealing to online supermarket non-users and lower the hurdle to use.

As a limitation of this study, since it targeted students of a specific Japanese university and the sample size was limited, there is a limit to generalization. However, we believe that this study has academic and practical significance in quantitatively showing a part of the actual usage and psychological characteristics of the target group of young Japanese adults, presenting future strategic challenges. In the future, we intend to advance research from both the consumer and corporate sides by conducting additional questionnaire surveys for young adults, as well as conducting surveys with online supermarket operators.

Acknowledgments

We would like to express our sincere gratitude to everyone who participated in the questionnaire survey for this study. This work was supported by JSPS KAKENHI Grant Number 24K05055.

References

[1] Kawabe, N. - *The Formation and Development of Online Supermarkets: The Integration of Virtual and Real Businesses* - The Waseda Commercial Review, volume 429. ISSN 0387-3404. [page 23-78]. September 2011 (in Japanese)

[2] https://www.super.or.jp/?page_id=4223 - 2023 Supermarket Annual Statistical Survey Report. 10-12.2025 (in Japanese)

[3] https://www.jetro.go.jp/ext_images/_Reports/02/2018/af3d253a6ebee696/br_super.pdf - Survey on the Online Supermarket Market in the UK. 10-12.2025 (in Japanese)

[4] https://www.stat.go.jp/data/sekai/pdf/2024al.pdf - World Statistics. 10-12.2025 (in Japanese)

[5] https://www.super.or.jp/?page_id=6709 - 2024 Supermarket White Paper. 10-12.2025 (in Japanese)

[6] Nakamura, M. - *A Study on Consumer Usage Behavior and Future Business Operations of Online Supermarkets* - Chukyo Business Review, volume 41. ISSN 1348-8848. [page 33-61]. December 2019 (in Japanese)

[7] Shigeta, T., Sakaue, T., & Suzuki, N. - *Changes in Consumer Behavior of University Students during COVID-19 Self-Restraint Period* - Journal of Information Systems & Operations Management, volume 18 no. 2. ISSN 1843-4711. [page 185-198]. December 2024

[8] Koyama, S., Sakaue, T., & Suzuki, N. - *Changes in Behavior of University Students after COVID-19 Self-Restraint Period* - Journal of Information Systems & Operations Management, volume 19 no. 1. ISSN 1843-4711. [page 162-177]. May 2024

[9] Jusoh, Z., & Ling, G. - *Factors Influencing Consumers' Attitude Towards E-Commerce Purchases Through Online Shopping* - International Journal of Humanities and Social Science, volume 2 no. 4. ISSN 2220-8488. [page 223-230]. February 2012

[10] Nakano, S., & Kondo, H. - *Temporal Changes in Consumers' Online Purchasing and Their Factors: Perspectives on Purchasing Characteristics and E-Commerce Usage Devices* - The Japanese Journal of Behaviormetrics, volume 46 no. 1. ISSN 03855481. [page 19-31]. 2019 (in Japanese)

[11] Ibrahim, N. A. N., Husseini, F., Aisyah, N., Camelia, N., Khazlyn, N., & Faiz, W. - *Online Shopping Behaviour in Youth: A Systematic Review of The Factors Influencing OnlineShopping in Young Adults* - International Jounal of Academic Research in Business & Social Sciences, volume 13, no. 2. ISSN 2222-6990. [page 157-166]. February 2023

[12] Jung-Im, S. - *An Empirical Investigation of Online Grocery Shopping Behaviors Based on Different Generations* - International Journal of Business and Management, volume 19, no. 1. ISSN 1833-3850. [page 185-196]. January 2024

[13] Moriuchi, E., & Takahashi, I. - *Satisfaction Trust and Loyalty of Repeat Online Consumer within the Japanese Online Supermarket Trade* - Australasian Marketing Journal, volume 24, no. 2. ISSN 1441-3582. [page 146-156]. May 2016

[14] Takahashi, I. - *Online Supermarkets as Innovators* - Marketing Journal, volume 36 no.2. ISSN 0389-7265. [page 5-20]. September 2016 (in Japanese)

Bibliography

Herbert, A, S. - *The Sciences of the Artificial (3rd edition)* - ISBN 9780585360102. Published by MIT Press. 1996

Ibrahim, N. A. N., Husseini, F., Aisyah, N., Camelia, N., Khazlyn, N., & Faiz, W. - *Online Shopping Behaviour in Youth: A Systematic Review of The Factors Influencing OnlineShopping in Young Adults* - International Jounal of Academic Research in Business & Social Sciences, volume 13, no. 2. ISSN 2222-6990. [page 157-166]. February 2023

Jung-Im, S. - *An Empirical Investigation of Online Grocery Shopping Behaviors Based on Different Generations* - International Journal of Business and Management, volume 19, no. 1. ISSN 1833-3850. [page 185-196]. January 2024

Jusoh, Z., & Ling, G. - *Factors Influencing Consumers' Attitude Towards E-Commerce Purchases Through Online Shopping* - International Journal of Humanities and Social Science, volume 2 no. 4. ISSN 2220-8488. [page 223-230]. February 2012

Kawabe, N. - *The Formation and Development of Online Supermarkets: The Integration of Virtual and Real Businesses* - The Waseda Commercial Review, volume 429. ISSN 0387-3404. [page 23-78]. September 2011 (in Japanese)

Koyama, S., Sakaue, T., & Suzuki, N. - *Changes in Behavior of University Students after COVID-19 Self-Restraint Period* - Journal of Information Systems & Operations Management, volume 19 no. 1. ISSN 1843-4711. [page 162-177]. May 2024

Moriuchi, E., & Takahashi, I. - *Satisfaction Trust and Loyalty of Repeat Online Consumer within the Japanese Online Supermarket Trade* - Australasian Marketing Journal, volume 24, no. 2. ISSN 1441-3582. [page 146-156]. May 2016

Nakamura, M. - *A Study on Consumer Usage Behavior and Future Business Operations of Online Supermarkets* - Chukyo Business Review, volume 41. ISSN 1348-8848. [page 33-61]. December 2019 (in Japanese)

Nakano, S., & Kondo, H. - *Temporal Changes in Consumers' Online Purchasing and Their Factors: Perspectives on Purchasing Characteristics and E-Commerce Usage Devices* - The Japanese Journal of Behaviormetrics, volume 46 no. 1. ISSN 03855481. [page 19-31]. 2019 (in Japanese)

Nonaka, I., & Takeuchi, H. - *The Knowledge-creating Company* - ISBN 9780195092691. Published by Oxford University Press, Inc. 1995

Satou, I. - *The Art & Science of Social Research, vol. 1* – ISBN 9784130520263. Published by The University of Tokyo Press. 2015 (in Japanese).

Satou, I. - *The Art & Science of Social Research, vol. 2* - ISBN 9784130520270 . Published by The University of Tokyo Press. 2015 (in Japanese).

Shigeta, T., Sakaue, T., & Suzuki, N. - *Changes in Consumer Behavior of University Students during COVID-19 Self-Restraint Period* - Journal of Information Systems & Operations Management, volume 18 no. 2. ISSN 1843-4711. [page 185-198]. December 2024

Sukegawa, M., Hatsushio, K., & Suzuki, N. - *Reconsideration of Long-term Internships and Future Proposals* - Journal of Information Systems & Operations Management, volume 18 no. 1. ISSN 1843-4711. [page 261-275]. May 2024

Takahashi, I. - *Online Supermarkets as Innovators* - Marketing Journal, volume 36 no.2. ISSN 0389-7265. [page 5-20]. September 2016 (in Japanese)

Tamura, M. - *Foundations of Causal Process Tracing* – ISBN 9784561267836. Published by Hakuto-Shobo. 2023 (in Japanese).

Thomas, S. K. - *The Structure of Scientific Revolutions 50th Anniversary Edition (4th Edition)*. ISBN 9780226458120. Published by The University of Chicago Press. 2012

https://www.jetro.go.jp/ext_images/_Reports/02/2018/af3d253a6ebee696/br_super.pdf - Survey on the Online Supermarket Market in the UK. 10-12.2025 (in Japanese)

https://www.stat.go.jp/data/sekai/pdf/2024al.pdf - World Statistics. 10-12.2025 (in Japanese)

https://www.super.or.jp/?page_id=4223 - 2023 Supermarket Annual Statistical Survey Report. 10-12.2025 (in Japanese)

https://www.super.or.jp/?page_id=6709 - 2024 Supermarket White Paper. 10-12.2025 (in Japanese)

INTEGRATION OF ARTIFICIAL INTELLIGENCE IN THE INTERNAL MANAGERIAL CONTROL OF EDUCATIONAL INSTITUTIONS AND IMPLICATIONS ON INTERNAL AUDIT

Georgiana Janina SOARE[1]

Abstract:
The research study is dedicated to the integration of Artificial Intelligence (AI) in the Internal Managerial Control System (IMCS) of educational institutions and analyzes the impact of this approach on internal audit. The main objective of the paper is to investigate how Artificial Intelligence technologies can be applied within the Internal Managerial Control System (IMCS) and in Internal Audit, in order to increase operational efficiency, transparency in resource management and the responsiveness of management structures to risks and non-conformities. The paper addresses both a theoretical and an applicative component, proposing concrete and empirically validated solutions. Specific applications of AI in the field of managerial control are presented – from risk identification and analysis to performance and compliance monitoring in the educational and financial activities of public entities in education. The research discusses the role and functionalities of Generative Artificial Intelligence (GAI) in Internal Managerial Control, its use in Internal Managerial Control in the field of education and the implications for internal audit. Technological solutions are also proposed as ways to use GAI in the implementation of Internal Managerial Control Standards in educational institutions.

Keywords: artificial intelligence, generative artificial intelligence (GAI), internal managerial control, internal audit, continuous audit, educational institutions, risks, compliance.

JEL Classification: M42 – Auditing

1. Introduction

In an era where technology is becoming increasingly ubiquitous and increasingly important for decision-making and management processes, educational institutions are faced with complex challenges in terms of resource management, performance monitoring and risk management. In this context, optimizing the Internal Managerial Control becomes essential to ensure an efficient and accountable internal audit in the education sector. The Internal Managerial Control System (IMCS) in educational institutions represents a fundamental element, providing an institutional and procedural framework for evaluating and improving internal audit and internal control processes. However, there are still significant challenges in implementing and streamlining the IMCS in educational institutions, including the lack of an integrated approach and the lack of adequate resources for implementation. By integrating AI (Artificial Intelligence) technologies into the Internal Managerial Control processes, the research study aims to provide innovative and effective solutions for

[1] PhD assistant, University Spiru Haret, Faculty of Economic Sciences Câmpulung Address: 223 Traian Street,115100 Câmpulung, Argeș, România, Corresponding author: georgiana.soare@spiruharet.ro

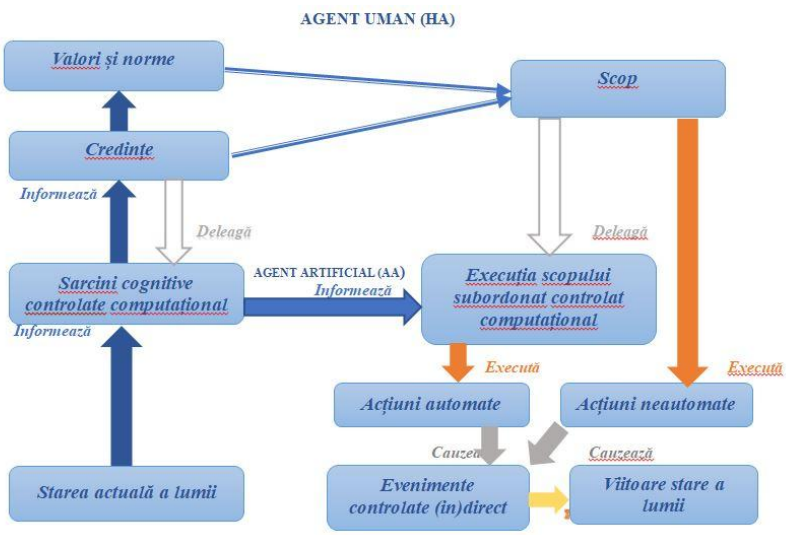
improving internal audit in educational institutions. The aim is not only to identify and remedy existing deficiencies in current practice but also to anticipate and manage future risks associated with the management of educational resources.
In the context of accelerated digitalization, Generative Artificial Intelligence (GAI) opens new horizons for optimizing Internal Managerial Control (IMC) and internal audit processes in educational institutions. GAI technologies offer advanced analysis and automation capabilities that can transform the way educational institutions manage and monitor internal activities, contributing to increased efficiency and improved organizational performance. The integration of Generative Artificial Intelligence into Internal Managerial Control in educational institutions represents a major opportunity for the transformation and optimization of internal processes, with a direct impact on internal audit, the quality of the educational act and resource management. As technology evolves, it is important that the research and implementation of these solutions continue, to ensure continued adaptability and efficiency in the face of emerging challenges.

2. Literature review

Artificial Intelligence (AI) refers to the ability of a system to process information from the external environment, learn from it, and apply the acquired knowledge to solve a variety of tasks (Zemánková, 2019) [1]. AI also involves the use of large data together with machine learning (ML) to make predictions about the future based on information from the past (Zhang et al., 2020) [2]. The ability of AI to perform tasks similar to those of humans is fueled by its ability to learn from mistakes and adapt to new input data. Through AI solutions, large volumes of data can be analyzed to identify recurring patterns in the data (Lee and Tajudeen, 2020) [3]. AI has gained popularity recently, with the increasingly widespread implementation of these solutions by various entities (Mann, D. L., 2023) [4]. AI solutions are considered sophisticated enough to replace human labor and speed up work processes and data accuracy. However, to be successful, organizations must overcome certain obstacles. AI is often perceived as expensive and risky to implement, as it is a new technology and managers do not always have the skills and knowledge to adopt it (Davenport and Ronanki, 2018). In addition, there are concerns about the possible negative effects of AI on society, such as job losses and increased unemployment. Adopting AI requires well-trained staff with the essential knowledge to implement these solutions so that they can continue to learn and make correct decisions (Sutton et al., 2018) [5]. In the field of accounting, AI leads to the reduction of repetitive tasks, the extraction of data from printed documents using technologies such as optical character recognition (OCR) or intelligent document processing (IDP) and their integration directly into accounting software (Sutton et al., 2016) [6]. It also generates a variety of financial reports, which help accountants become financial experts and support clients in making various business decisions, such as business expansion through mergers and acquisitions (Mihai, 2023) [7].
In accounting and auditing in educational institutions, the integration of Artificial Intelligence (AI) can represent a significant step towards modernizing and streamlining financial and Internal Managerial Control processes. By using advanced data analysis algorithms, AI can quickly identify anomalies, trends, or patterns that may be difficult to detect through traditional methods. This can lead to greater accuracy and reliability of financial information and more efficient management of the financial resources of educational institutions. In the context of changing concerns in social and political sciences,

new Internal Managerial Control practices have emerged, while technological advances such as computers and the Internet have introduced new technologies for Internal Managerial Control. With recent advances in Artificial Intelligence (AI), especially in Machine Learning (ML) and Large Language Processing (LLP), it is unlikely that accounting and auditing activities will retain their current form and practice in the next decade. In the face of these recent advances, the question for Internal Managerial Control and accounting professionals is not whether the subject matter of study will change, but where and how it might be interesting to study changes within Internal Managerial Control. Although automation is not a new concept, the nature of the tasks that are now targeted and the scalability of the automation process may be different (Susskind, R. E. & Susskind, D. (2015).) [8]. Therefore, automation remains a critical topic for accounting and auditing research. For accounting professionals, potential areas of interest for critical research include, for example: what new tasks and coordination concerns arise around automated processes (Samiolo et al., 2023) [9], what types of tasks are automated (Korhonen et al., 2020) [10], what are the forms and sources of resistance to automation (McDaid et al., 2023) [11], "what happens to the boundaries and relationships between accounting and other professions" (Armstrong, 1985) [12], and documenting and critically analyzing the impact of automation on accounting practices, both inside and outside organizations (Salijeni et al., 2019), [13]. Although concerns about automation have dominated the debates, the more significant aspects of AI development revolve around machine learning (ML) models and Large Language Processing (LLP). Because ML technology offers new analysis possibilities, it also brings a significant change in practice - the analysis process is, at least partially, automated and is becoming increasingly advanced. Here, the introduction of Artificial Intelligence raises questions about a new type of coordination in accounting and auditing practice, namely how to align "machine intelligence" with the knowledge and tacit judgment of people in the organization (Kilfoyle et al., 2013) [14]. While it is recognized that managers rely on different sources of information outside of accounting (Hall, 2010), [15], the introduction of ML tools puts entity leaders (or the Internal Managerial Control System) in a position where they must coordinate different epistemological forms of analysis. The topic of automation and the role of AI in decision-making processes is closely related to the development of Generative Artificial Intelligence and AI applications in various fields. While the use of LLPs for building chatbots remains an interesting topic, the main focus has shifted to the ways in which deep learning models can be used for data analysis and to assist in decision-making. Because these approaches can involve chatbots as discussion partners, the automation of decision-making by delegating cognitive and decision-making functions from human agents to artificial agents is becoming a central concern in the evolution of Artificial Intelligence and human-machine interaction. By automation of decision-making, we understand the delegation of a subordinate cognitive or decision-making function from an agent capable of responsibility, i.e. a human, to a non-biological form of information, a process that was designed by a human specifying specific calculation rules. The human agent (HA) can delegate either cognitive tasks or the execution of subordinate tasks, or both, to an artificial agent (AA). In the field of accounting and auditing, the HA exercises direct control over its own actions and, at the same time, indirectly controls the actions of artificial agents (AA), establishing general objectives that govern the parameters and boundary conditions for their activity. Thus, the HA has the responsibility to ensure that the AA implements only the established accounting and

auditing requirements and standards, ensuring the integrity and accuracy of financial information. Figure 1 represents an idealized process of automation (Michele Loi, Matthias Spielkamp, 2021) [16] of both cognitive and executive functions. Blue arrows indicate information flow. White arrows indicate delegation. Gray arrows indicate causality. Arrows with oblique stripes denote execution.



Glossary:

AGENT UMAN (HA)- HUMAN A

Valori și norme - Values and norms

Scop - Goal

Credințe - Beliefs

Informează - Informs

Deleagă – Delegates

Sarcini cognitive controlate comput
Computationally controlled cogniti

AGENT ARTIFICIAL (AA) - ART
AGENT (AA)

Execuția scopului subordonat contr
computațional - Execution of subor
computationally controlled goal

Execută - Executes

Acțiuni automate - Automatic actio

Acțiuni neautomate - Non-automat

Starea actuală a lumii - Current stat
world

Cauzează - Causes

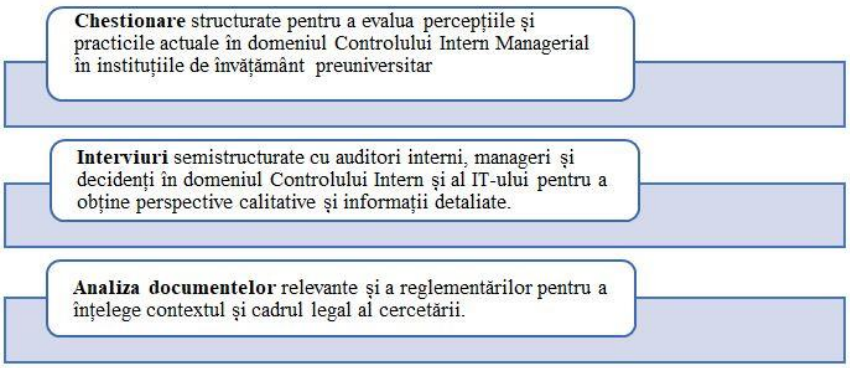
Evenimente controlate (in)direct - (
controlled events

Viitoare stare a lumii - Future state

Figure 1. Decision-making automation process
Source: Michele Loi, Matthias Spielkamp, 2021.

3. Research methodology

The methodology used in the research to investigate the optimization of Internal Managerial Control and, implicitly, internal audit, through the use of Artificial Intelligence technologies in educational institutions is summarized in choosing a mixed approach, combining theoretical research and applied research to obtain a comprehensive understanding and to validate the proposed solutions. Type of research: qualitative and quantitative research to examine the theoretical and practical aspects related to Internal Managerial Control, internal audit and the use of Artificial Intelligence in the context of accounting in educational institutions. The instruments used for data collection in the study were structured questionnaires, semi-structured interviews and document analysis (Figure 2).



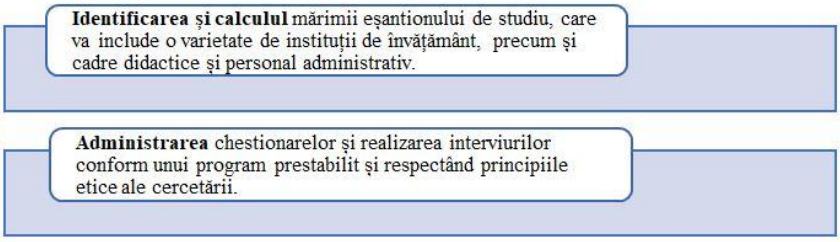
Structured **questionnaires** to assess current perceptions and practices in the field of Internal Managerial Control in pre-university educational institutions

Semi-structured **interviews** with internal auditors, managers and decision-makers in the field of Internal Control and IT to obtain qualitative perspectives and detailed information.

Analysis of relevant **documents** and regulations to understand the context and legal framework of the research.

Figure 2. *Data collection instruments*
Source: own design

The data collection procedure consisted of identifying the study sample, administering questionnaires and interviews and collecting responses (Figure 3).



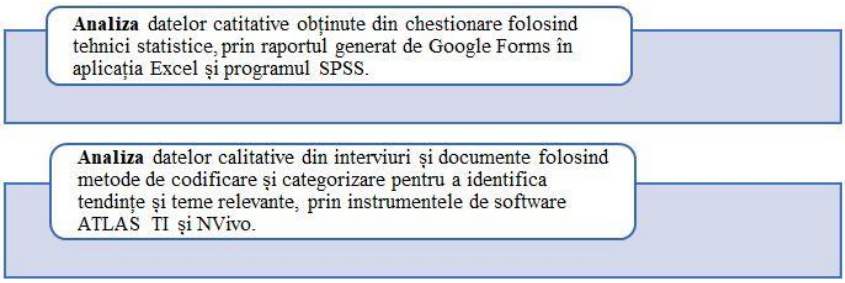
Identifying and calculating the size of the study sample, which will include a variety of educational institutions, as well as teaching and administrative staff.

Administering questionnaires and conducting interviews according to a pre-

established schedule and respecting the ethical principles of research.

Figure 3. *Data collection procedure*
Source: own design

The analysis of the collected data was carried out through specific analysis programs (Figure 4).

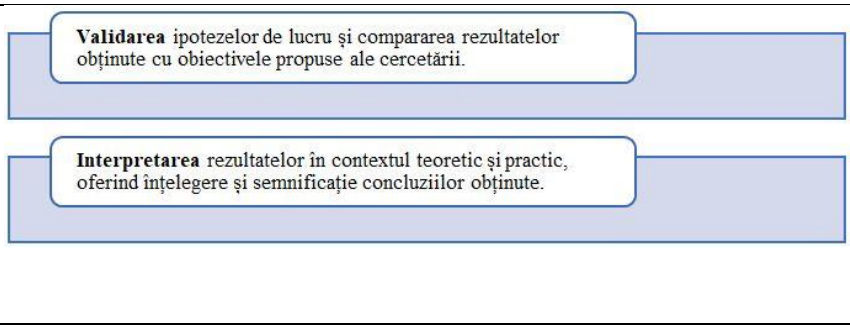


Analysis of quantitative data obtained from questionnaires using statistical techniques, through the report generated by Google Forms in the Excel application and the SPSS program.

Analysis of qualitative data from interviews and documents using coding and categorization methods to identify relevant trends and themes, through the ATLAS TI and NVivo software tools.

Figure 4. *Data analysis methods*
Source: own design

Validation or invalidation of hypotheses was a fundamental process in research that involved assessing the degree to which the collected and analyzed data support or contradict the statements formulated in the research hypotheses (Figure 5).



Validation of working hypotheses and comparison of the results obtained with the proposed objectives of the research.

	Interpretation of the results in the theoretical and practical context, providing understanding and significance to the conclusions obtained.

Figure 5. *Validation and interpretation of data*
Source: own design

4. The need to integrate AI into the Internal Control of educational institutions

Internal Control is essential for good governance and the efficient functioning of an educational institution. The integration of intelligent technologies into Internal Control could represent a significant advance for educational institutions. Through AI, they can strengthen their ability to identify and manage risks, to comply with internal and external regulations and policies, and to improve their overall performance. In the context of educational institutions, where organizations operate in complex and rapidly evolving environments, the importance of effective Internal Control is essential. This control represents the backbone of risk management, financial integrity, and regulatory compliance. The emergence of Artificial Intelligence (AI) presents an unprecedented opportunity to revolutionize Internal Control mechanisms, leveraging AI's analytical prowess, pattern recognition capabilities, and automation potential to enhance effectiveness and efficiency. Internal Control is a comprehensive framework designed to ensure the achievement of organizational objectives by mitigating risks, increasing operational efficiency, and safeguarding assets. Integrating AI into Internal Control processes can bring substantial benefits in various areas: *Data Analysis and Pattern Recognition*: AI excels at analyzing large amounts of data quickly and accurately. It can identify patterns, correlations, and anomalies in financial transactions, flagging potential issues that might be missed by manual analysis. *Predictive Analytics*: By leveraging historical data, AI can predict potential risks and trends, allowing institutions to proactively address emerging challenges before they escalate. *Automate routine tasks*: AI-powered automation can streamline repetitive tasks such as data entry, reconciliation, and report generation. This not only reduces human error, but also frees up human resources for strategic efforts. *Fraud detection*: Advanced AI algorithms can analyze financial data for suspicious transactions and behaviors, playing a critical role in early fraud detection. Natural Language Processing (NLP): NLP equips AI to analyze unstructured data such as emails, contracts, and textual information. It helps identify compliance violations, unethical behaviors, and unusual communication patterns. *Continuous monitoring*: AI enables real-time or near-real-time monitoring of transactions and processes, ensuring prompt identification of irregularities and deviations. *Customizable alerts*: "Organizations can configure AI systems to generate alerts based on predefined criteria, ensuring that exceptions are promptly brought to attention" (V. Gaddam, 2024). Implementing Artificial Intelligence in Internal Control in educational institutions is essential for streamlining administrative processes and effectively managing resources. With the help of AI, institutions can quickly identify potential problems, such as financial management or absenteeism monitoring, and make more informed and faster decisions. *Implementing AI in Internal Control processes requires*

a strategic approach (Figure 6.), which involves: *Needs Assessment*: Identifying areas where AI can have the most significant impact, whether it is automating manual tasks, strengthening data analysis, or improving fraud detection. *Data Preparation*: Clean, structured, and accurate data is essential for AI effectiveness, and its quality must be ensured before being introduced into AI models. *AI Solution Selection*: Opting for AI solutions that align with the institution's needs and capabilities could involve developing internal solutions or purchasing third-party applications. *Training and Integration*: Training AI models with historical data to adjust their predictions can seamlessly integrate AI into existing systems and workflows. *Continuous Improvement*: Regularly evaluating the insights generated by AI and adapting models as the business landscape evolves, as well as continuously refining AI performance through feedback loops.

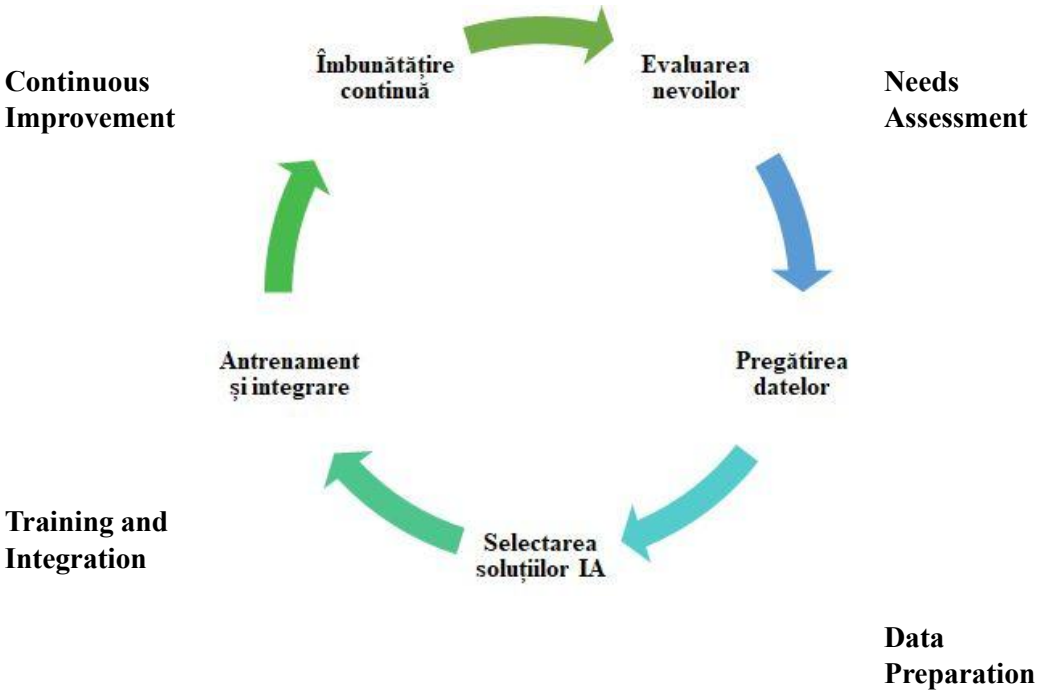


Figure 6. *Strategic Approach to Implementing AI in Internal Control*
Source: Own design

Integrating Artificial Intelligence into Internal Control processes is akin to introducing a revolutionary agent that improves accuracy, efficiency, and foresight. The fusion of AI capabilities – data analytics, predictive analytics, automation, and more – with the core principles of internal controls is a powerful formula for addressing the complexity of the educational institution environment in the digital age. While AI offers immense promise, it should be seen as an augmentation rather than a replacement for human judgment, vigilance, and ethics. By embracing the potential of AI and fostering a culture of vigilant

oversight, organizations can truly revolutionize their Internal Control landscapes for the better (Gaddam, 2023) [17].

4.1. The Contribution of Artificial Intelligence in Achieving the Objectives and Goals of IMCS in the Context of Digitalization of Education

Adapting education to Artificial Intelligence (AI) is a vital process in modern society; involving not only the integration of digital technologies into educational processes but also a reconfiguration of the way in which education and training are designed, delivered and evaluated. In this context, the contribution of Artificial Intelligence (AI) in the Internal Management Control System (IMCS) is becoming increasingly relevant, offering significant opportunities for optimizing administrative and managerial processes in educational institutions. Adapting the education and training system to technological evolution is a complex process, essential for the preparation and improvement of human resources and for the development, modernization and innovation of society. The integration of new digital technologies makes school more attractive for students, more adapted to their needs and lifestyle and more efficient in developing skills, promoting lifelong learning. The impact of digital transformation on society, the labor market and education and training systems is becoming increasingly evident. The digital transformation in education is driven by advances in connectivity, the widespread use of digital devices and applications, the need for individual flexibility and the increased demand for digital skills. "The Covid-19 crisis has transformed educational practices from face-to-face interaction to the online environment, underlining that teaching, learning and emerging technology must be approached holistically in the future of digital education. This has highlighted the importance of digital education as a central objective for high-quality, accessible and inclusive teaching, learning and assessment, as well as the need for a strategic approach to the acquisition of digital skills throughout life for all participants" (SMART-Edu, Strategy for the Digitalization of Education in Romania 2021-2027). The digital transformation in education, accelerated by the Covid-19 crisis, has highlighted the need for an integrated and strategic approach in adopting emerging technologies to meet the needs and requirements of contemporary education. It is important that adaptation to technological evolution also extends to related or bordering areas, such as the Internal Managerial Control System (IMCS) in digital education, which must also be digital in its turn. When referring to the digitalization of education, it is essential to recognize that this does not only represent a transition to online teaching but also a fundamental transformation of educational processes. In this sense, the integration of AI in the educational IMCS can facilitate the efficient management of data and administrative processes, contributing to the optimization of resources and the improvement of the quality of educational services. Starting from the digitalization of education, the mission of the educational institution, as well as its objectives, must ensure the need for the technologization of education in all its aspects, so that IMCS is an essential tool for managing a school towards fulfilling its mission and achieving the established objectives, ensuring efficient, transparent and responsible management of the institution's resources and activities. The concretization of a school's mission is done through a set of measurable and verifiable objectives that allow for the evaluation and control of performance. From a time perspective, the objectives are classified, according to Figure 7.

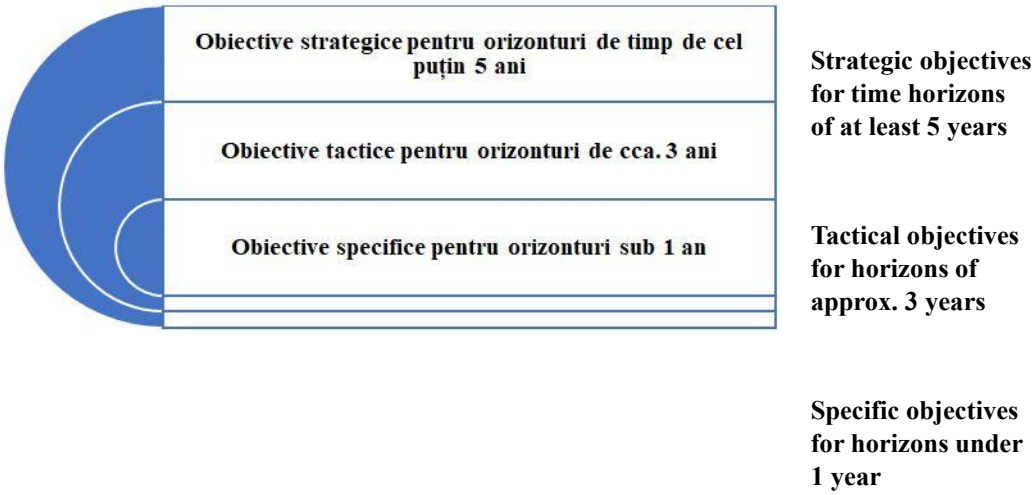


Figure 7. *Classification of objectives by duration*
Source: own design

Within educational units, objectives target certain functional areas whose detailed enumeration provides a comprehensive perspective on the various aspects that must be managed for the proper functioning of the institution. In the context of the Internal Managerial Control System (IMCS), these areas become essential for ensuring the coherence, efficiency and effectiveness of administrative and managerial processes:

1. FUNCTIONAL AREA: MANAGEMENT
• Ensuring managerial coherence at the level of the school unit through specific steps;
• Increasing the efficiency of the activity of functional departments in the school unit;
• Efficient functioning of the education quality management system in the school unit.

2. FUNCTIONAL AREA: CURRICULUM
• Designing the curriculum in accordance with the methodological requirements in force.
• Diversifying teaching-learning-evaluation methods in order to apply the curriculum in the classroom based on modern techniques with the aim of individualizing and differentiating learning with the aim of acquiring key European competences.
• Periodic evaluation of school progress and school performance and using the results to increase the quality of the teaching process.
• Designing a flexible and attractive SCD (School-Decided Curriculum) offer, correlated with the options/interests of students and the possibilities of professional insertion on the labor market.
• Designing an offer of extracurricular educational activities appropriate to the training needs of young people.
• Increasing the degree of participation of teachers and students in training programs for school performance, formal and non-formal education;
• Increasing the degree of school integration of students from disadvantaged social groups.
• Correlating the annual school plan with the options/interests of students and with the possibilities of professional insertion on the labor market.

3. FUNCTIONAL AREA: HUMAN RESOURCES
• Correct application of legal provisions regarding the employment of qualified teaching, auxiliary and non-teaching staff.
• Promoting human resources management that ensures the increase in quality and the efficiency of the overall activity of the school unit.
• Ensuring access of school personnel to training appropriate to the application of the requirements of the education system and its adaptation to the European one.
• Improving internal and external communication.
• Strengthening the Internal Managerial Control System.
• Identifying and resolving problematic situations among students, by ensuring specific psycho-pedagogical counseling services, school and professional orientation.
4. FUNCTIONAL AREA: MATERIAL RESOURCES
• Continuing the efforts to modernize and preserve the school infrastructure, creating its specific facilities.
• Monitoring the updating of the teaching and material base in the school, in accordance with the standards of the curricular efforts.
• Efficient management of existing resources.
• Involving local public authorities in activities to improve the school infrastructure.
• Submitting financing projects for the development of material and human resources.
• Developing material resources in order to make the educational process more efficient.
5. FUNCTIONAL AREA: COMMUNITY AND PARTNERSHIP RELATIONS (EDUCATIONAL PROJECTS AND COMMUNITY PROGRAMS)
• Strengthening collaboration with the local public authorities: Town Hall and Local Council, Police, Gendarmerie, ISU, NGOs, Parents' Association, trade union, in order to ensure an attractive, safe and functional school environment.
• Development of educational projects by promoting formal and non-formal educational activities aimed at developing intercultural, entrepreneurial education, health education and those that can provide the necessary support in promoting school desegregation and equalization of opportunities.
• Increasing institutional capacity and ability to develop and manage projects financed by community programs for human resources development, through projects/grants financed by structural funds and through projects of the Ministry of Education and Research in order to develop institutional and create optimal conditions for the development of lifelong education and the diversification of educational offers and services.
• Enhancing the activity of the Commission for International Partnerships and Programs by developing skills in project drafting and project management.
• Streamlining the activity of the Commission for School and Extracurricular Educational Programs.
• Managing the image of the institution, promoting its image through institutional and educational marketing.
• Developing the school-family partnership. (System Procedure for Setting School Objectives, 2018).

By adopting AI technology, educational institutions can benefit from a number of advantages that allow them to better align with the current needs and requirements of

students, teachers and the community as a whole. AI can contribute to achieving specific objectives in the functional areas of a school and thereby support IMCS processes:
1. *Efficient management*: AI can be used to optimize school resource management processes, including human and material resources. By analyzing data and usage patterns, AI can provide recommendations for a more efficient allocation of resources and to identify opportunities to improve efficiency in different departments and school activities.
2. *Adapted and diversified curriculum*: The use of AI can allow the curriculum to be personalized according to the individual needs and interests of students. By analyzing their performance and preferences, AI can suggest personalized content and teaching methods, thus contributing to increasing engagement and academic performance.
3. *Continuous monitoring and evaluation*: AI can facilitate the process of monitoring and evaluating the academic progress of students and the performance of teachers. By analyzing data obtained from various sources, AI can identify relevant trends and patterns, providing feedback and recommendations for improving individual performance and educational processes as a whole.
4. *Improved communication and collaboration*: The use of AI can facilitate communication and collaboration between different stakeholders within the school community, including students, teachers, parents and local authorities. Through AI-based platforms and applications, tools and facilities can be provided that allow for more effective communication and closer collaboration in order to achieve common educational goals.
5. *Community and partnership relationship management*: AI can contribute to the development and strengthening of collaborative and partnership relationships between the school and the various organizations and institutions in the community. By analyzing data and identifying opportunities for collaboration, AI can facilitate initiatives to involve the community in educational activities and support the school's objectives.

4.2. Application of Generative Artificial Intelligence in internal managerial control in educational institutions

4.2.1. The Role and Functionalities of Generative Artificial Intelligence in Internal Managerial Control in Educational Institutions

The possibility of integrating Generative Artificial Intelligence (GAI) into the Internal Managerial Control of educational institutions brings to light multiple benefits, starting with streamlining processes, improving communication and providing constant support for all those involved in the school community. By analyzing the benefits and potential of GAI in this context, we will outline a complete picture of the contribution of these emerging technologies (chatbots) to the modernization and streamlining of Internal Managerial Control in education. A chatbot is a computer application specialized in simulating conversations with human users, predominantly via the internet. These systems rely on technologies such as Artificial Intelligence and machine learning to interpret and respond to user questions and requests. When used within the framework of Internal Managerial Control activities, chatbots, as tools of GAI, bring multiple benefits, including: *Increased efficiency*: Chatbots can handle a large volume of questions and requests in a short time, freeing up staff time for other activities. *Improved accessibility*: Users can interact with the chatbot at any time of the day or night, without being restricted by personal schedules or staff availability. *Consistent responses*: Due to their automated nature, chatbots provide consistent and accurate answers to frequently asked questions, eliminating possible

discrepancies or human errors. *Continuous improvement*: By learning from previous interactions, chatbots become more efficient and accurate in providing answers as they accumulate more data and experience. "The key elements of GAI are: interaction: communicates with users via text or voice. automation: automatically generated responses, without constant human intervention. adaptability: learns from interactions to improve future responses. How a chatbot works: Input: the user enters a question or command. Processing: the chatbot analyzes the request using NLP (Natural Language Processing) algorithms. Response: generates an appropriate response based on the analysis performed. Technological leaps that have led to more sophisticated chatbots: Advanced Algorithms: the refinement of algorithms that allow chatbots to understand and process human language with increasing accuracy. Learning capabilities: machine learning has allowed chatbots to adapt and improve based on previous interactions. Multidimensional interaction: current chatbots can handle multiple tasks and provide almost human conversational experiences" (Andrei Pojoreanu, 2023) [18].

The key elements of a chatbot and its functionalities can be adapted for use in Internal Control in the field of education in several ways, as follows: *Standard 12 – Information and communication. Adapted interaction*: the chatbot can communicate with teachers, students and parents via text or voice, giving them the opportunity to ask questions, receive information and request assistance on various issues related to school administration. *Standard 9 – Procedures. Automation of administrative processes*: the chatbot can automate administrative processes, such as filling out forms, managing appointments for meetings or providing information on the internal procedures of the educational institution. *Standard 8 – Risk management. Adaptability and lifelong learning*: by using machine learning algorithms, the chatbot can learn from previous interactions and improve its responses according to the needs and preferences of users, developing measures for existing risks. *Standard 10 - Supervision. Efficient management of requests and complaints*: the chatbot can process and direct requests and complaints received from users to the relevant departments within the educational institution, ensuring that they are resolved in a reasonable and efficient time. *Standard 11 – Business continuity. Assistance for the online learning process*: in the context of distance learning, the chatbot can provide technical assistance and information about online learning platforms, accessing educational resources and using digital tools. *Standard 15 – Evaluation of the Internal Managerial Control System*. *Generation of reports and analyses*: the chatbot can generate the annual evaluation report using the feedback received and the problems identified, providing the leaders of the educational institution with valuable information to improve internal processes. "Considering the contribution of GAI in process management, it has become a fundamental tool in the arsenal of any modern entity, not just a technological trend, but an effective way to improve various aspects of monitoring a system, by integrating a chatbot into the Internal Control of educational institutions, communication, information management and feedback collection can be streamlined, thus contributing to improving transparency and accountability in educational administration" (Andrei Pojoreanu, 2023) [18]. Among the existing chatbots, ChatGPT stands out for its remarkable performance in natural language processing and its advanced adaptability and continuous learning capabilities, making it an ideal choice to be integrated into the Internal Control of educational institutions. "ChatGPT is an artificial intelligence language model developed by OpenAI. GPT stands for generative pre-trained transformer. A transformer is a specific class of neural networks that

is pre-trained, meaning trained on huge amounts of past observations. Being generative refers to the step-by-step generation of ChatGPT tokens (a group of characters, such as a word or part of a word. (https://platform.openai.com/tokenizer (Figure 8.). This is to see how words are divided into tokens, the units that ChatGPT works with, to build sentences, paragraphs, or entire articles of text based on the learned predictive distribution of tokens (previously generated or provided tokens). Chat means that the transformer has been optimized for conversational chat. ChatGPT was launched on 11/30/2022 and had one million users in five days (by comparison, Instagram took two and a half months to reach the same user base), making it the fastest growing consumer app to date" (M.Hofert, 2023) [19].

Figure 8. *Tokenizer Example*
Source: OpenAI

To highlight the contribution that ChatGPT can make to the implementation and compliance of *Standard 8 – Risk Management within an educational institution*, the results of the case study *ChatGPT Competencies Assessment in Quantitative Risk Management*, conducted in May 2023, by Marius Hofert [19], were analyzed. The study investigates to what extent ChatGPT can understand concepts in the field of risk, risk measures, time series, extremes and dependence. The study's conclusions show that non-technical aspects of risk (such as explanations of different types of financial risk, the factors underlying the 2007-2009 financial crisis, or a basic introduction to the Basel Framework[2]) are well understood by ChatGPT. More technical aspects (such as mathematical facts) are often inaccurate or wrong, sometimes in quite subtle ways. Guidance is provided on the types of applications for which consulting ChatGPT can be useful in improving knowledge about quantitative risk management in actuarial practice and those for which ChatGPT should not be invoked

[2] Basel is an international regulatory framework that aims to strengthen regulation, supervision, and risk management in the banking sector.

are highlighted (M.Hofert, 2023) [19]. Based on the conclusiveness of the results of this study, we will consider the main conclusions about the use of ChatGPT in risk management, in order to serve the present research, by adapting it to the needs of IMCS in school education. Analyzing the results of the presented study, we conclude that the ChatGPT Generative Artificial Intelligence technology can make a significant contribution to the identification of unknown risks and in risk management in the educational field. Due to its ability to be trained on sources covering risks that educational institutions have not previously encountered or cannot anticipate, ChatGPT can detect those unknowns that may represent latent threats to institutions. This approach is similar to the introduction of operational risk loss databases in the financial industry, where companies use this data for internal stress tests, in order to identify and effectively manage risks. Using ChatGPT in this context, of implementing and complying with Standard 8, is more accessible not only to large institutions but also to smaller institutions. Institutional leaders seeking an impartial perspective on measures can request recommendations from ChatGPT. Although the answers generated by GAI may sometimes be inconclusive, the introduction of these aspects into risk management brings a new and necessary perspective, thus contributing to a holistic approach to risk management in education.

4.2.2. Similarities between the use of Generative Artificial Intelligence (GAI) in finance and that of Internal Managerial Control in educational institutions

GAI use in finance:
Financial virtual assistants, known as chatbots, are programs based on Generative Artificial Intelligence that interact with customers via text or voice and provide financial services. These chatbots are useful for banks and other financial institutions, allowing them to provide 24/7 customer service, automate repetitive tasks, and improve user experience. Some common applications of chatbots in finance (Table 1) include account management, providing customer service, and offering investment advice. In general, chatbots in the financial sector help companies reduce costs, improve efficiency, and provide a more pleasant experience for their customers. These are just a few examples of how chatbots are being used in the financial industry to provide convenient and efficient services to customers" (Geerling, Mateer, Wooten, & Damodaran, 2023) [20].

Table 1. *Examples of chatbots in the financial industry*

The name of the chatbot	The financial utility
HSBC's Amelia	A virtual assistant that can help customers with account management, money transfers, and investment advice.
Chase's CoiN	A chatbot that helps customers with account questions, card activation, and fraud alerts.

Citi's Virtual Assistant	A chatbot that helps customers with account management, balance inquiries, and bill payments.
Erica from Bank of America	A virtual financial assistant that helps customers manage their accounts, pay bills, and make budget plans.
Capital One's Eno	A chatbot that helps customers check account balances, view transactions, and receive fraud alerts.
Ally Assist	A virtual assistant offered by Ally Bank that helps customers with account management, bill payments, and investment advice.
TD Ameritrade Chatbot	A virtual assistant that provides real-time market information and investment recommendations.
American Express Virtual Assistant	A chatbot that helps cardholders manage their accounts, track rewards, and get customer service.
Fidelity Virtual Assistant	A chatbot that helps customers with investment advice, account management, and research.

Source: own design

In the context of an accelerated digital transformation, "numerous uses for Generative Artificial Intelligence can be found in the different areas of the financial sector, along the entire value chain, from back-office to middle-office to front-office. Some applications aim to improve the customer experience (e.g. biometric authentication), while others aim to optimize and/or transform processes in the different stages of the provision of financial services (e.g. using new data sources for investment selection or determining risk premiums). Combining Generative Artificial Intelligence with other technologies (such as distributed ledger technology and smart contracts) can further increase the possibilities. Without being exhaustive, the following examples of the use of Generative Artificial Intelligence in the financial sector can be highlighted: *Chatbots and virtual assistants*. They allow users to resolve common doubts and, in some cases, provide product recommendations or carry out certain transactions (e.g. order transfers, open accounts).

Customer communication channels thus become automated, meaning they are available 24/7 and, in addition, data on user interactions is automatically collected. *Personalization of end products and services*. Based on information obtained from customers, financial institutions are able to offer a personalized user experience, possibly even beyond banking services in the strictest sense of the term (for example, sending account balance alerts if geolocation services detect that customers are making purchases). *Anti-money laundering and fraud prevention controls*. The ability to analyze a larger volume of data and combine this data with new sources of information allows for the detection of anomalies or patterns that would otherwise have gone unnoticed. It also significantly reduces the number of false alarms, making fraud and anti-money laundering control tasks faster and more accurate, with less customer disruption. *Credit scoring*. Increased analytical capacity can improve credit assessment and accelerate credit origination. In addition, the use of unstructured data can increase the number of eligible customers, making this analysis easier for new financial institutions or those operating in new markets about which little information is available. *Regulatory compliance*. The greater analytical capacity offered by artificial intelligence tools makes it easier to comply with certain regulatory requirements (e.g. risk management, reporting obligations) and also to monitor regulatory changes" (Fernández, 2019) [21]. Starting from the examples of use of GAI in the financial field, we can highlight its potential in Internal Control in educational institutions, by implementing Internal Managerial Control standards in several ways, according to Table 2.

Table 2. *Ways of using GAI in the implementation of Internal Managerial Control Standards*

Components of Internal Managerial Control	*Internal Managerial Control Standards*	*Examples of using GAI in the implementation of standards*
Control environment	*STANDARD 1 ETHICS AND INTEGRITY*	Artificial Intelligence can be used to monitor employee behavior and identify potential violations of the code of ethics.
	STANDARD 2 ATTRIBUTES, FUNCTIONS, TASKS	Artificial Intelligence systems can help to assigning tasks and responsibilities effectively, ensuring that each team member has the right role and responsibilities.
	STANDARD 3 COMPETENCE, PERFORMANCE	Artificial Intelligence can assess employee competencies and provide recommendations for their professional development based on the specific needs of the organization.
	STANDARD 4 ORGANIZATIONAL STRUCTURE	Artificial Intelligence systems can analyze and optimize the organizational structure to ensure effective communication and equitable distribution of responsibilities.

Performance and Risk Management	*STANDARD 5 OBJECTIVES*	Artificial Intelligence can contribute to defining and monitoring organizational objectives, automatically identifying discrepancies and suggesting necessary adjustments.
	STANDARD 6 PLANNING	Artificial Intelligence systems can assist in developing action plans and allocating resources based on identified priorities and risks.
	STANDARD 7 PERFORMANCE MONITORING	Artificial Intelligence can automatically monitor the organization's performance and generate periodic reports for high-level management.
	STANDARD 8 RISK MANAGEMENT	Artificial Intelligence systems can automatically identify and assess potential risks, as well as provide recommendations for measures to manage them.
Control Activities	*STANDARD 9 PROCEDURES*	Artificial Intelligence can automate internal processes and procedures, ensuring their consistent and accurate application.
	STANDARD 10 MONITORING	Artificial Intelligence systems can monitor the organization's activities in real time and can automatically alert on any anomalies or deviations from established procedures.
	STANDARD 11 BUSINESS CONTINUITY	Artificial Intelligence can contribute to the planning and implementation of business continuity measures, automatically identifying vulnerabilities and proposing backup solutions.
Information and communication	*STANDARD 12 INFORMATION AND COMMUNICATION*	Artificial Intelligence systems can facilitate internal and external communication through chatbots and other voice or text-to-speech assistance technologies.
	STANDARD 13 DOCUMENT MANAGEMENT	Artificial Intelligence can efficiently manage organizational documents, including their automatic indexing, searching and archiving.
	STANDARD 14 ACCOUNTING AND FINANCIAL REPORTING	Artificial Intelligence Systems can automate the financial and accounting reporting process, ensuring accuracy and compliance with accounting standards.
Evaluation and Audit	*STANDARD 15 EVALUATION OF THE INTERNAL MANAGERIAL CONTROL SYSTEM*	Artificial Intelligence can evaluate the efficiency and effectiveness of the Internal Managerial Control System by analyzing operational data and performance indicators.

	STANDARD 16 INTERNAL AUDIT	Artificial Intelligence Systems can assist internal auditors in identifying risks and deviations, as well as in developing recommendations for improving organizational processes.

Source: own design

4.2.3. The Use of Generative Artificial Intelligence in Internal Managerial Control in Education and Implications for Internal Audit

In recent years, the use of Generative Artificial Intelligence (GAI), especially ChatGPT, has become increasingly widespread in a variety of fields, this technology bringing with it a series of benefits and challenges for education, research and the business environment. ChatGPT has been applied in a variety of academic and non-academic fields to analyze contributions and risks and to take appropriate measures. For example, it can be used to monitor patients remotely by analyzing data from sensors or other monitoring devices, providing real-time information about a patient's health status. In other research, it can improve the productivity and efficiency of accounting professionals by transforming their work systems. Also, some researchers have highlighted the ability of ChatGPT to generate short stories based on the information provided by the user. Entities have used ChatGPT to improve the way people work by automating repetitive tasks and providing more engaging interactions with users. Institutions have integrated ChatGPT into various aspects of their operations, including creating marketing content, generating unique ideas, writing computer code, automating steps in the sales process, providing customer aftercare, translating text between languages, and increasing customer engagement.

"While the media and blogs have covered various aspects of the use of ChatGPT in education, a systematic review of the impact of the technology on multiple aspects of education and research is needed" (Cribben and Zeinali, 2023) [22]. In the 2023 case study, titled "The benefits and limitations of ChatGPT in business education and research: a focus on management science, operations management and data analytics," the researcher examines the use of ChatGPT by both faculty and students. In terms of education, ChatGPT can be a versatile tool for teachers and students. Teachers can use it to create course materials, curricula, tests and exams, and to assist in student assessment and understanding. For students, it can provide explanations of complex concepts and help them with various tasks, such as writing and debugging code or preparing for exams. In general, ChatGPT's abilities in writing and debugging code, as well as in assessment, are considered its strengths in the field of education and research. However, the use of Artificial Intelligence has generated controversy in the academic environment, as it seems to change the current way the education system works. "It is essential to establish clear guidelines to maximize the benefits of this tool in the academic environment, including guiding teachers in its appropriate use and their role in guiding students in the appropriate and responsible use of the platform, also considering ethical aspects, such as the possibility of bias and plagiarism" (Cribben and Zeinali, 2023) [22].

In the context of Internal Managerial Control in educational institutions, the use of ChatGPT can bring significant benefits. Teachers and teaching staff can use this technology to streamline management and evaluation processes. Through ChatGPT, they can create course materials, study programs and evaluation tools, thus contributing to ensuring

managerial coherence and the efficiency of the activity of functional departments in the educational unit. ChatGPT can also be useful in identifying unknowns in the context of Internal Managerial Control. Through its ability to understand and answer various questions, ChatGPT can help identify potential risks or generate solutions to the problems faced by the educational unit. This can contribute to strengthening the Internal Managerial Control System and improving the efficiency of Internal Audit. The use of ChatGPT in Internal Managerial Control also raises some ethical and practical issues that need to be addressed. It is important that teachers and teaching staff are prepared to use this technology responsibly and guide students in its appropriate use. It is also necessary to have clear guidelines for the use of ChatGPT in the educational context, so as to maximize its benefits and minimize the associated risks. Given the aspect of using chatbots in the teaching-learning-evaluation process, the Internal Managerial Control System of educational institutions should consider, by complying with the Internal Control Standards, adapting both the objectives and the existing operational procedures to respond to the imposed changes. Of course, the inclusion of chatbots in the IMCS implementation can be considered, in order to improve control activities. For example, involving the help offered by Generative Artificial Intelligence (GAI) in the application of *Standard 14 - Financial and accounting reporting* in educational institutions, can bring significant benefits in streamlining processes and improving the quality of financial reports. By using GAI in this context, educational institutions can perform faster and more accurate analyses of financial data, more easily identifying trends and anomalies, thus providing a clearer and more comprehensive picture of their financial situation. "The use of Artificial Intelligence techniques in the provision of financial services can increase efficiency, reduce costs, improve quality, increase the level of satisfaction of beneficiaries and stimulate financial inclusion, mainly due to the possibilities they offer for automating operational processes and increasing analytical capacity. Techniques such as natural language processing or image recognition allow institutions to automate repetitive or low-value-added tasks, such as answering frequently asked questions. Through automation, the potential for human error is reduced, productivity is increased and the costs associated with these tasks are reduced. As a result, the level of satisfaction of GAI users increases, as they receive more efficient services, with shorter response times and higher service availability. By saving costs through automation, institutions can also offer certain services that were traditionally available only to a limited number of beneficiaries, now being extended to a wider range of users. This expansion of access to services can contribute to increasing user satisfaction and improving institutional efficiency. Thanks to Artificial Intelligence tools, institutions are able to analyze a much larger volume of structured and unstructured data much faster. In addition, the increased number of variables increases the quality of the analysis, as the knowledge of the beneficiaries is greater and the results obtained are more accurate. All of the above is to the advantage of all the factors involved, as it allows institutions to provide better services, in compliance with regulations. In addition, a greater analytical capacity allows institutions to exploit all the data (both internal and external) to which their beneficiaries have access, to learn more about their preferences. In this way, they are able to develop personalized products and services and even anticipate needs, improving the user experience" (Fernández, 2019) [21]. One of the main advantages of integrating GAI into financial and accounting reporting is its ability to process and analyze large volumes of data in a much shorter time than a human team could. Machine learning algorithms can

identify patterns and correlations in financial data, helping to detect fraud or accounting errors and thus providing additional assurance that financial reports are accurate and reliable. GAI can also be used to automate repetitive processes within financial reporting, such as reconciling accounts or generating standardized reports. By eliminating manual and repetitive tasks, accounting staff can be freed up to focus on value-added activities, such as data analysis or developing financial strategies. Another benefit of integrating GAI into financial and accounting reporting is its ability to provide predictive analytics and data-driven recommendations. By analyzing historical data and identifying trends, GAI can help educational institutions better anticipate and manage financial risks and make more informed decisions regarding budget planning and investments. However, integrating GAI into financial and accounting reporting also poses some challenges for Internal Audit. First, auditors need to adapt their approaches to assess the effectiveness of using GAI in institutional processes. This includes verifying the accuracy and reliability of data generated by GAI, ensuring that these technologies are used ethically and responsibly, and assessing their impact on existing internal controls. In addition, the audit must ensure that data used by GAI is protected in accordance with security and confidentiality standards and that the risks associated with the use of this technology are appropriately managed. Integrating IAG into the Internal Managerial Control processes of educational institutions, including financial and accounting reporting, thus brings both considerable benefits and new challenges that need to be carefully managed by Internal Audit. It is essential that auditors to update their methods and knowledge to be able to effectively oversee the use of these technologies and to ensure that they contribute to improving the governance and performance of institutions.

5. Conclusions

The research highlighted that, in most educational institutions, IMCS and Internal Audit are implemented in a formal and traditional manner, but not sufficiently efficient. Although there are documented procedures and established organizational frameworks, modern automation and monitoring tools are lacking. This reality generates high resource consumption, operational risks not identified in time and a limited capacity to react to non-conformities. Artificial Intelligence technologies, especially Generative AI (GAI), have proven their potential to contribute significantly to the optimization of IMCS and Internal Audit. By analyzing the data obtained from IT specialists and accountants, the idea that AI can automate repetitive tasks, identify patterns and irregularities difficult to observe through conventional methods and support data-driven decision-making was clearly outlined. Thus, AI brings considerable added value to decision-making and control processes. AI can actively support the achievement of IMCS objectives by strengthening the capacity of institutions to assess risks, anticipate deviations and implement effective corrective measures. The use of AI in internal audit has demonstrated increased accuracy in detecting errors and fraud, as well as a superior capacity to analyze financial flows, compared to classic methods. This contribution is essential for increasing the robustness of control systems and strengthening institutional accountability. The integration of AI into audit processes has led to a visible streamlining of activities. The research validated the fact that AI allows for a rapid, complete and permanent verification of documents and financial processes, favoring the transition from a reactive to a continuous audit. This transformation

is particularly important in the current context of the digitalization of public administration and the need to adapt educational institutions to modern governance standards.

References

[1]. Zemánková, A. (2019). Artificial intelligence and blockchain in audit and accounting: Literature review. Transactions on Business and Economics, 16(1), 568-581.
[2]. Zhang, Y., Xiong, F., Xie, Y., Fan, X., & Gu, H. (2020). The impact of artificial intelligence and blockchain on the accounting profession. IEEE Access, 8, 110461-110477. https://doi.org/10.1109/ACCESS.2020.3000505.
[3]. Lee, C.S., & Tajudeen, F.P. (2020). Usage and impact of artificial intelligence on accounting: Evidence from Malaysian organizations. Asian Journal of Business and Accounting, 13(1). https://doi.org/10.22452/ajba.vol13no1.8
[4]. Mann, D.L., (2023). Artificial Intelligence Discusses the Role of Artificial Intelligence in Translational Medicine. JACC: Basic to Translational Science. https://doi.org/10.1016/J.JACBTS.2023.01.001 .
[5]. Sutton, S.G., Arnold, V., & Holt, M. (2018). How much automation is too much? Keeping the human relevant in knowledge work. Journal of emerging technologies in accounting, 15(2), 15-25, https://doi.org/10.2308/jeta-15(2) .
[6]. Sutton, S.G., Holt, M., & Arnold, V. (2016). "The reports of my death are greatly exaggerated"—Artificial intelligence research in accounting. International Journal of Accounting Information Systems, 22, 60-73. https://doi.org/10.1016/j.accinf.2016.07.005
[7]. Mihai, M. S. (2023). O analiză cantitativă referitoare la impactul soluțiilor Inteligenței Artificiale în contabilitate şi audit. Audit Financiar, XXI, No. 3 (171)/2023, 377-392. Available at: https://revista.cafr.ro/ArticolRO?CodArticol=9729 (Accessed on: 14.02.2025).
[8]. Susskind, R. E. & Susskind, D. (2015). The future of the professions: How technology will transform the work of human experts. Oxford: Oxford University Press
[9]. Samiolo, R., Spence, C. & Toh, D. (2023). Auditor judgment in the fourth industrial revolution. Contemporary Accounting Research.
[10]. Korhonen, T., Selos, E., Laine, T. & Suomala, P. (2020). Exploring the programmability of management accounting work for increasing automation: An interventionist case study. Accounting, Auditing & Accountability Journal.
[11]. McDaid, E., Andon, P. & Free, C., (2023). Algorithmic management and the politics of demand: Control and resistance at Uber. Organizations and Society Accounting
[12]. Armstrong, A.B., (2023). Who's Afraid of ChatGPT? An Examination of ChatGPT's Implications for Legal Writing. SSRN Electronic Journal. https://doi.org/10.2139/SSRN.4336929 .
[13]. Salijeni, G., Samsonova-Taddei, A. & Turley, S. (2019). Big Data and changes in audit technology: Contemplating a research agenda. Accounting and Business Research, 49(1), pp. 95-119.
[14].Kilfoyle, E., Richardson, A. J. & MacDonald, L. D. (2013). Vernacular accountings: Bridging the cognitive and the social in the analysis of employee-generated accounting systems. Accounting, Organizations and Society, 38(5), pp. 382-396.

[15]. Hall, M. (2010). Accounting information and managerial work. Accounting, Organizations and Society, 35(3), pp. 301-315
[16]. Loi, M. & Spielkamp, M. (2021). Towards accountability in the use of Artificial Intelligence for Public Administrations. AlgorithmWatch. Available at: https://algorithmwatch.org/en/wp-content/uploads/2021/05/Accountability-in-the-use-of-AI-for-Public-Administrations-AlgorithmWatch-2021.pdf (Accessed on: 13.02.2025).
[17]. Gaddam, V. (2023). Revolutionizing Internal Controls and Harnessing AI's Potential. Linkedin. Available at: https://www.linkedin.com/pulse/revolutionizing-internal-controls-harnessing-ais-potential-gaddam/ (Accessed on: 13.02.2025).
[18]. Pojoreanu, A. (2023). Chatbot: Cum poate această tehnologie revoluționa compania ta. GRANTS NEWS. Available at: https://aigrants.eu/chatbot/ (Accessed on: 15.02.2025).
[19]. Hofert, M. (2023). Assessing ChatGPT's proficiency in quantitative risk management. SSRN. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4444104 (Accessed on: 15.02.2025).
[20]. Geerling, W., Dirk Mateer, G., Wooten, J. & Damodaran, N. (2023). ChatGPT has Mastered the Principles of Economics: Now What?. SSRN. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4403372 (Accessed on: 03/01/2025).
[21]. Fernández, A. (2019). Artificial intelligence in financial services. SSRN. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366846 (Accessed on: 16.02.2025).
[22]. Cribben, I. & Zeinali, Y. (2023). The benefits and limitations of ChatGPT in business education and research: a focus on management science, operations management and data analytics. SSRN. Available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4404276 (Accessed on: 16.02.2025).

Bibliography

Davenport, T. H. & Kim, J. (2013). Keeping up with the quants: Your guide to understanding and using analytics. Boston, MA: Harvard Business School Publishing Corporation.
Gaddam, V. (2023). Revolutionizing Internal Controls and Harnessing AI's Potential. Linkedin. Available at: https://www.linkedin.com/pulse/revolutionizing-internal-controls-harnessing-ais-potential-gaddam/ (Accessed: 13.02.2024).
Regulation of December 20, 2022 regarding the activity of External Public Audit, approved by DECISION no. 629 of December 20, 2022, published in the Official Gazette of Romania, Part I, no. 12 of 5 January 2023. Available at: https://legislatie.just.ro/Public/DetaliiDocument/263698 (Accessed on: 9.05.2025).
EU 2024/1689 Regulation of the European Parliament and of the Council of 13 June 2024 laying down harmonized rules on Artificial Intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 (Law on Artificial Intelligence). Available at: https://www.mcid.gov.ro/wp-content/uploads/2024/01/Strategie-Inteligenta-Artificiala-22012024.pdf (Accessed on: 6.08.2025).
Current Affairs European Parliament. (2023). Artificial Intelligence: Opportunities and Dangers. Available at:

https://www.europarl.europa.eu/news/ro/headlines/society/20200918STO87404/inteligenta-artificiala-oportunitati-si-pericole (Accessed on: 03.02.2025).
Charter of Internal Audit exercised at the level of the Ministry of National Education, (2024). MEN. Internal Audit Department. Available at: https://www.edu.ro/sites/default/files/CARTA%20%20AUDITORULUI.pdf (Accessed on: 9.05.2025).
ChatGPT, O. A. A. & Perlman, A., (2022). The Implications of OpenAI's Assistant for Legal Services and Society. SSRN Electronic Journal. doi:10.2139/SSRN.4294197.
Deloitte, (2019). Refocus your robotic process automation lens: Internal control over financial reporting (ICFR) considerations for developing and implementing bots.
Internal Control System Evaluation Guide in Public Institutions, according to the MPFO 946/2005, (2024). Blogger. Available at: https://control-intern.blogspot.com/2012/01/definirea-sistemului-de-control-intern.html (Accessed on: 17.01.2025).
SMART-Edu, Strategy for the Digitalization of Education in Romania 2021-2027.

System Procedure for Setting the Objectives of an Educational Institution, 2018.

RESHAPING NONVERBAL COMMUNICATION IN A BUSINESS ENVIRONMENT RULED BY VIRTUAL MEETINGS

Georgiana SURDU[1]
Valeriu POTECEA[2]

Abstract

Depending on the context, some people can send mixed messages when it comes to nonverbal communication. For this reason, it is important to understand nonverbal communication and our own errors or limitations.

Think about a recent conversation you had where you felt it was important to get your point across. Was the response you received the way you wanted it to be? The response is often a reflection of the message you sent. Nonverbal behaviors can mirror each other and reveal the relationship between two people.

Nonverbal elements are a part of us, a subtle representation of our thoughts and emotions. And yet, most people have no idea what it conveys. We are so focused on choosing the right words that we forget what message our body is sending.

In this article, we aim to explore the psychological and communicative issues caused by virtual nonverbal deficits and how users can adapt to maintain connection and mutual understanding online.

Key words: nonverbal communication, virtual meetings, negotiation, technology

JEL Classification: D91, D74, M10

Discussion

Communication can be considered a fundamental characteristic of human existence. All managerial functions are carried out with the help of communication, as a process of understanding between people through the transfer of information.

In business contexts, for instance during the negotiation process, a person sends and receives messages, sends stimuli and collects responses. The messages sent or received can be verbal, paraverbal or non-verbal and must be deciphered as best as possible by the negotiators.

[1] Lecturer, PhD, School of International Business, Romanian-American University, e-mail: georgiana.surdu@rau.ro, corresponding author
[2] Professor, PhD, School of International Business, Romanian-American University, email: valeriu.potecea@rau.ro

We can communicate using languages, symbols and signs, which can be verbal and non-verbal. We communicate non-verbally even by our simple presence (how we look) or through the things around us (how we choose or arrange them). We communicate in this way without wanting to and without realizing it. It is practically impossible to block non-verbal communication, as we can with verbal communication.

In the 60's, two researchers, A. Mehrabian and M. Weiner (1967) [1] found that the proportion in which we use verbal language and nonverbal languages is, in oral communication, the following:

- ✓ 7% words
- ✓ 38% paralanguage (mainly intonation and voice inflections)
- ✓ 55% of other elements of nonverbal language (mainly facial expression, gestures and body posture).

Even it is considered controversial, because, among others, their study included only women, it is still quoted on a large scale in the academic environment. Extraordinary communicators deliberately use nonverbal cues and paralanguage because they know they can make a difference in how they are perceived by others.

Nonverbal communication can support, contradict or substitute verbal communication, regulate and control it (for example, through gestures that symbolize the desire to take over the conversation, approval/disapproval, encouraging the interlocutor to speak, etc.). The nonverbal message is closest to the reality of the sender and is the one to which the interlocutor pays the most attention.

There are several types of nonverbal communication. One type is sensory nonverbal communication, which is based on what we receive through the senses of sight, hearing, smell, touch and taste. Another type is aesthetic nonverbal communication (painting, music, dance, image, etc.), which takes place through different forms of artistic expression and communicates different artistic emotions. Another nonverbal communication is based on the use of insignia (flags, badges, uniforms, etc.) and specific symbols such as, for example, those related to religion (cross, altar, icons, etc.) or social status (officer ranks, decorations, titles, etc.). Interpreting nonverbal language is often challenging and several aspects must be considered. To avoid misinterpretation of a nonverbal element, it must be analyzed in the context of all other verbal and nonverbal elements that accompany the message. Also, a correct interpretation requires considering factors such as the individual's personality, level of education, life experience and other relevant personal characteristics. In addition, the way nonverbal language is used and interpreted differs significantly not only from one person to another, but also from one profession to another, from one community to another and from one culture to another, which requires caution and flexibility in their analysis.

To improve our ability to communicate through nonverbal languages, we must first become aware of how we ourselves use and interpret these languages and their impact on those around us.

We all use gestures, but sometimes we're not very good at matching our gestures to what we have to say. Intentional gestures support the message and keep the listener's attention.

According to S. Sayler (2011) [2], gestures add a kind of visual momentum, which is often useful so that you don't have to repeat yourself. For example, a curious side effect of counting nonverbally is that the audience will remember which finger refers to the sales report and which to the budget review. Often listeners will use the exact same fingers when delivering the message.

Sociometric research shows that humans subconsciously assess hierarchy within seconds because high status individuals exhibit distinct nonverbal patterns.

High-power individuals tend to adopt relaxed, slightly asymmetrical postures, while low-power individuals tend to make themselves smaller and more symmetrical (for example tightly folded hands or feet glued together)

Mirroring is formally known as behavioral synchrony, as when two people are aligned or like each other, they subconsciously match each other's posture, gestures and speech rates. But this process must happen naturally, don't try to imitate someone, the response will be one of distrust. Instead, try to match their energy level and posture within 15-30 seconds, to create a sense of shared goals.

Often a group of people make a joint decision that the group members, as individuals, would consider unacceptable, but is not a decision that anyone individually wanted.

Thus, each member of the group makes the decision that they believe the others want, giving up the decision that they would have made individually - the result being that the group decides to do something that no one actually wanted to do, but something that seemed to please the other members of the group.

This phenomenon occurs in any type of group, whether it is a formal group (committee, council, etc.), or whether it is an informal group, a group of friends or family members.

Thus, the group accepts decisions that members would not make individually, because each of the group members believes that they can evade responsibility, which falls on the group, not on an individual level.

Moreover, no one really feels solidarity with the decision made, respectively no one is willing to assume the consequences of the decision made in the group.

It usually appears because of an internal communication problem in the group, with each member refraining from presenting and supporting their own opinion because they believe it would be averse to the wishes of the other members and do not want to be making a discordant note or opposing the general good.

A classic example of mirroring is the Abilene Paradox, defined in 1974 by Jerry B. Harvey, an American management professor, and is considered the cause of very bad group

decision-making in certain situations, due to the conformism and desire for group membership of its members.

But today's reality is much different from that of 10 years ago, the widespread use of technology has brought a new complexity to the communication process. Shifting nonverbal communication from physical boardrooms to digital spaces introduces significant friction. In a virtual interaction, our brains work much harder to process human connection due to fatigue and data deprivation. In his work, The Art of Public Speaking, Stephan E. Lucas claims that on average, a person speaks at a rate of 120-150 words per minute, but the brain can process between 400-800 words in the same minute, which means that the process of listening and observing is more tiring than the process of speaking.

When we move meetings to a screen, the information stream gets compressed, chopped up, and distorted. This friction is a primary driver behind “zoom fatigue”, because our brains must work twice as hard to decode what used to be subconscious information [3].

It is difficult to look someone in the eyes and look at your camera at the same time and is hard to read their facial reactions. In face-to-face conversations, typical response pauses are a mere 200 milliseconds, while video conferencing tools introduce tiny audio and video delays (vary from 300 to 700 milliseconds). Such delays make us perceive the speaker as less friendly, less focused and more anxious.

Also, it’s an intimacy paradox because we place our faces much closer than we would normally stand in an office, and that can trigger a fight or flight response in some people, as it is perceived as forced intimacy. For many people it is stress caused by the need to be groomed, to wear make-up, to look nicer, almost like TV presenters.

Software platforms introduced beauty filters that smooth out skin and adjust low light. Our aesthetic became subtly airbrushed in real time. However, we must be careful in using some functionalities. Too much filter sends a message of superficiality and frivolity, we do not focus on important things such as preparing the communication, but rather on superficial aspects.

Personal appearance communicates through body shape of clothing, smell (aroma, flavor), jewelry and other accessories.

By what we communicate, based on certain attitudes and preconceptions that we have, body shape (tall, thin, thin wrists, reduced muscle mass, fat free, short, athletic, broad shoulders, muscles well represented, nonfat) is an important element to be realized in the evaluation made by others.

A person who looks good is automatically associated with a person having social success. Clothing reflects the personality of the individual, is a kind of extension of the self, and in this context, communicates information about it.

It can even affect our general behavior or of others. Clothing can also be used to create a role or social status real or pretended.

For business meetings and negotiations, the clothing should be simple, elegant and of good quality. But the traditional corporate dressing changed quickly after 2020, the traditional suits and crisp looks were replaced by a new philosophy: business on the top, pajamas on the bottom.

And once this happened, even the office aesthetic changed towards more comfortable clothing, less structured, minimalist. But few people understand that this aesthetic is part of nonverbal communication, and the way we dress sends a message.

Of course, for some, seeing a CEO in a hoodie having a video call from his house democratized the workplace. In their eyes, the person became more relaxed, empathetic and vastly more human.

But this image is misleading, because in face-to-face meetings, negotiations or conferences, these CEOs return to tailored-made suits, nonverbally they want to convey a message of power.

We communicate a lot through body movements and gestures, and in a video conference we are reduced to "talking heads". This leaves teams operating with a massive deficit in emotional context, at a time when more companies are reducing their travel expenses and conducting negotiations online.

Nonverbal element	Face to face meeting	Online meeting
Eye contact	Looking directly at the person's face, and adapting your gaze to context	The 70/30 rule: look at the camera 70% of the time when speaking, and at the screen 30% of the time to read reactions.
Gestures	Free movement, gestures naturally visible, without exaggerating.	Position your camera so your shoulders and hands are visible. Keep gestures within the lower third of the camera frame.
Active listening	Head nods, subtle vocal cues.	Use slightly larger nods and visible facial expressions, micro-expressions get lost in low video resolution.

Posture	Natural sitting or standing	Lean slightly towards the camera to show more engagement, while slouching backward makes you look detached.

Table 1. How to adapt your nonverbal communication to online business meetings

Source: adapted from Webb, M., Zoom fatigue and how to prevent it, PMC, 2023

These changes in communication have brought both good points for business negotiations, but also less favorable aspects. From our personal experience we can say negotiations are more fragmented today. Someone can have a video conference to negotiate a contract, and at the same time team members message each other privately on WhatsApp to coordinate counter offers.

This way of approaching negotiation does not lead to immediate decisions; it is a sequential approach to some problems. Between these video conferences, a series of summarizing and clarifying emails are exchanged. Negotiations take longer and give partners time to change their minds, what we don't always want from our partner or in critical situations for our company.

These pauses can have a positive effect as well, because we are not forced into concessions immediately, we have time to simulate scenarios, to consult with experts from our company, and it reduces the emotional pressure.

Table 2. Traditional negotiations versus virtual negotiations

Analyzed factor	Traditional negotiations	Virtual negotiations
Nonverbal communication	Full body language, a connection can be created, less communication errors.	Limited to head and shoulders, artificial contact, hard to read the room.
Logistics & costs	Can be expensive and tiring, and you work on a strict schedule.	Zero travel costs and highly adaptable but depends on the time zone and company rules regarding technologies.
Team coordination	Rely on subtle physical cues and eye contact. The preparation of the process is key. Based on empathy and emotional intelligence.	You can use private channels to text and align with the team. There may be more communication blunders.

		Less empathy and real connection.

Source: adapted from The Harvard Negotiation Project & Program on Negotiation research on "E-Negotiation"

Online or offline, communication can have many barriers, and especially nonverbal communication.

Very common in both mediums are the lack of attention, distraction of the receiver or irrelevance of the subject for it. For example, since the advent of mobile phones, especially smartphones, we are very distracted from communication. This distraction may be interpreted by the partner as a lack of respect or interest.

When we fail to provide nonverbal feedback, the speaker's brain interprets it as rejection. Also, research in social psychology shows that consistent lack of attention reduces the speaker's cognitive clarity, losing their train of thought [4].

Active listening is a skill that can be acquired and developed through practice. This skill can be difficult to master and will therefore take time and patience. Active listening involves listening with all your senses. In addition to paying close attention to the speaker, it is important that the "active listener" is also "seen" as listening - otherwise, the speaker may conclude that what they are saying is uninteresting to the listener. By providing this feedback, the speaker will feel more at ease and will therefore communicate more easily, openly and honestly. There are both verbal and non-verbal cues associated with active listening.

Non-verbal cues include smiling (if appropriate), direct eye contact, nodding at appropriate times and avoiding any distractions. These nonverbal cues convey the message that the other person is interested in what the speaker has to say and that their attention is fully engaged.

Giving verbal cues of active listening can also be helpful. Reflecting on what the speaker has said by asking a clarifying question can be one such cue. Paraphrasing involves finding slightly different words to restate the speaker's main idea and is also a great way to show active listening.

The language barrier plays a very important role in virtual meetings, because we tend to speak more than in face-to-face meetings, and we are more limited in gestures that can help us understand the message.

So, platforms such as Microsoft Teams, Zoom or Google Meet have implemented translation features that reduce the language barriers.

We have experienced in many virtual meetings that some teammates hold back and don't feel comfortable because they are not native speakers of English, for example.

This functionality also reduced costs, because now companies don't have to pay an interpreter or hire people that are bilingual or speak several languages.

Also, besides live translation, such platforms generate translated meeting transcripts and summaries, and participants can review it and analyze it later.

Another important barrier lies in cultural differences. The rules of social interaction vary greatly in different cultures, as does the expression of emotions.

Despite our digital savvy urban population and robust information technology sector, we would say that face to face communication remains an important mechanism for trust verification in the Romanian culture. Critical business milestones such as introductions, joint ventures or complex contracts are overwhelmingly conducted in person.

All these cultural differences extend to gestures, eye contact, even proxemics, or attitude towards time. Even during virtual meetings, we can observe different screen etiquette, camera behavior or verbal pacing.

In high-context cultures, having your camera on is essential, it builds trust and shows care for details and respect.

Also, many people observe the background of your screen and give meaning to it. A cluttered background can unintentionally signal disorganized thinking, while a sterile or blurred background can feel distant and impersonal. It is very important to adapt your background depending on the interlocutor, the stakes of the discussion, and preferably, important meetings should take place from the office, for a more professional and business-oriented image.

In some other cultures, low-context or very private, if the meetings are not high-level or a visual presentation is explicitly required, team members prefer to keep cameras off to protect their private space [5].

Many confusions can appear in virtual meetings because of cultural differences. For example, we experienced situations with Western partners that interpreted silence as a technical glitch, and not as a period for reflection.

We have also experienced situations where partners don't understand pauses and face expressions and end up talking over each other. And sometimes platforms like Zoom or Teams have audio algorithms that cut off one speaker when another speaks, creating a disruptive technical clash.

In our opinion, companies need to start simulating these online meetings, especially the high-stakes ones, just like face-to-face meetings, to avoid overlapping situations within their own team or technical problems.

At the same time, companies are already implementing online codes of conduct, safety measures regarding the technologies used or banning AI in these meetings. Also, for longer virtual meetings, sending the agenda is still a must, to prioritize topics to discuss and be time conscious.

Regardless of culture, many people tend to perform rather than communicate naturally, as seeing your own reflection so often causes hyper self-awareness. This problem can be solved by hiding their own self-view, you can only see the others and focus on them.

Another very important aspect that produced a total shift from traditional negotiations and communication norms are the proprietary selling and bidding platforms that eliminate human to human negotiations.

Driven by advancements in artificial intelligence, machine learning, and game theory, companies are transitioning from traditional communication and back-and-forth discussions to zero negotiation or autonomous negotiation models.

Such platforms operate under the "take it or leave it" business model. Buyers or sellers post a specific requirement alongside a calculated, data-driven price. Using AI powered matching features, qualified business partners can click "match" or "accept" to lock the contract.

Companies like Walmart or Maersk use AI platforms that use chatbots and automated agents that negotiate with thousands of suppliers at the same time. Clearly, the companies pre-set parameters like payment terms, quantity, discounts, delivery dates. It is a modern version of the traditional negotiation mandate.

Table 3. Advantages and disadvantages of algorithmic platforms in negotiations

Advantages	Disadvantages
You can cover more negotiations at the same time and optimize results by being data oriented.	Some businesses are resistant to algorithmic platforms, feeling squeezed by rigid parameters or alienated by the lack of human communication.
Reduce the negotiation time to minutes and give professionals time to focus on high-stakes negotiations and strategic relationships.	Automated bidding can turn transactions into rigid, price only battles. Even the most sophisticated technologies can have errors or misinterpretations of contractual clauses.
Algorithmic bidding eliminates human emotion, bias and fatigue from the process.	Removing human dialogue reduces collaborative problem-solving, where

	buyers and sellers find mutual value beyond just price.
Seamless ERP integration, as once the bid is accepted, the system automatically generates purchase orders, contracts, and syncs with enterprise resource planning systems.	Algorithmic platforms don't have contextual awareness of people, for example geopolitical changes, natural disasters, labor strikes, etc.

Source: adapted from Nibble Technology Whitepaper, The State of Autonomous Negotiation in Procurement, 2026

Resistance to change remains one of the most significant barriers to successful technology adoption in business communication. We shouldn't label those employees as old-fashioned or stubborn, because the root causes are deeply human.

For example, during pandemic, we all have become competent in Teams, Zoom, Google Meet and other platforms. But technology evolves very quickly, and we were saying that even these platforms added more functionalities, and this transforms us into novices again, the feeling of not knowing frustrates us.

During the pandemic, and even today, many employees mentioned to us that these modern communication tools feel like a "digital leash", because they have active statuses and tracking metrics, you need to stay "online". This is a very important aspect, because if the communicators have personal concerns and are stressed, they may be consumed by these personal concerns and will not be receptive to the message being conveyed. The psychological state of the business partners will influence how the message is received.

Maybe a potential solution to reduce the resistance to change would be, instead of training modules, implementation guides, and digital transformation managers, to work on the informal implementation. What we mean by informal implementation is using peer-to-peer learning, as employees are more comfortable asking a colleague about a new app than asking a manager. Every organization has early adopters of different apps and technologies; they naturally are inclined to use it. So, they can be empowered to promote it among colleagues in a subtle and gradual way.

Regardless of the means of communication, virtual or face to face, we suggest the message must be calibrated to the specifics of the audience, and easy-to-understand language is the best solution. Excessive use of specific terminology and professional jargon should be avoided. People are often intimidated by specialized language and are afraid to admit that they do not understand the message being delivered. The speaker can make a few deliberate pauses in the presentation to ask questions to ensure that the message is understood as intended. It will also allow the listener to ask clarifying questions.

Also, even though feedback given to the interlocutor may occasionally be negative, it is important that it be constructive in nature. Providing feedback helps to enhance the speaker's skills. This will strengthen interpersonal relationships and future communications.

Conclusions

Although technology has made the world smaller, enabling companies to be connected more easily and at any time, in many ways has made our cultural and communication differences more visible.

Virtual meetings on platforms such as Teams, Zoom or Webex, are stripping away subtle gestures, side glances, and ambient room energy.

Sometimes the communication seems very blunt, pauses feel longer and awkward and interruptions are more aggressive.

The transition to virtual meetings favored more low-context communicators, that are direct and explicit. In our opinion, companies must create virtual spaces/tools that allow less direct communicators to engage more.

Even the usage of communication platforms is different depending on geography. In North America and Europe, we use extensively Teams, Slack, Webex, WhatsApp for business negotiations, client management or daily updates on projects. But in China, for example, they use more WeChat and WeChat Work, and they don’t easily accept meetings on other platforms.

We tend to replace nonverbal communication with emojis in these online meetings, a phenomenon increasingly common among young professionals. But this approach can be misunderstood and viewed as unprofessional by partners from other countries, superiors, and more experienced colleagues.

We believe that we are still in a transitional or dualistic period, in which we must learn the secrets of nonverbal communication and subsequently adapt them to the specifics of virtual meeting.

For many companies, the way they negotiate reflects their brand values. If a company treats its partners as commodities squeezed by an algorithm, it may find it difficult to attract premium partners who want to work with collaborative, face to face communicators.

Also, by offloading negotiations to software, companies risk losing their internal talent, those skilled negotiators that can solve high-stakes negotiations.

Over the past few years, we have encountered many situations where partners we had collaborated with online, when they met us face to face, had reactions like "you're shorter than I imagined" or "you have a much firmer handshake than I imagined". These show us that for many business individuals, direct relationships are important.

Clearly is hard to signal warmth in virtual meetings, but it is not impossible. For example, when comes into a call, they should offer a genuine smile, this signals warmth and builds psychological safety. It should draw people into the conversation and make them feel seen and valued.

Depending on the goal of the meeting, colors can be used to project competence and warmth. For example, deep blues and navies are regarded as the trust colors, the person using them can, in this way, project reliability, professionalism and calm competence.

On the technical side, solid white reflects too much light, often blinding the camera lens and your face ends up in shadow. Tight stripes or busy patterns create a dizzying visual glitch on video. It looks like your clothes are vibrating or shimmering.

The most important rule of virtual wardrobe charisma is contrast. Aim to be a distinct shape against your background so that your physical movement and expressions remain clear.

A distinctive feature of face-to-face business meetings is the integration of socialization into professional frameworks. Those meetings transition from formal boardrooms to informal settings, like business lunches or dinners. These informal meetings allow business partners or even teammates to establish personal rapport, which builds long term business relationships. Also, in this relaxed environment more accurate data can be collected on people's nonverbal communication skills. Beyond what is said, the energy and charisma exuded play a significant role. Important decisions are still made considering the human factor.

References:

[1] Mehrabian, A., & Wiener, M., Decoding of inconsistent communications. Journal of Personality and Social Psychology, 6(1), 1967

[2] Sharon Sayler, What Your Body Says (And How to Master the Message): Inspire, Influence, Build Trust, and Create Lasting Business Relationships, 2011, Wiley Publishing

[3] N. Bailenson, Nonverbal overload: A theoretical argument for the causes of Zoom Fatigue, Technology, Mind and Behavior, 2021

[4] Williams, K.D, Ostracism, Annual Review of Psychology, 2007

[5] Stahl, G.K, Maznevski, M.L, Unraveling the effects of cultural diversity in teams: A retrospective of research on multicultural groups, Journal of International Business Studies, 2021

Bibliography

1. The Harvard Negotiation Project & Program on Negotiation research on "E-Negotiation"
2. Webb, M., Zoom fatigue and how to prevent it, PMC, 2023
3. Nibble Technology Whitepaper, The State of Autonomous Negotiation in Procurement, 2026
4. Bhattacharyya S, Tariq S, Frameworks for organizational digital transformation and the role of change management, Journal of Strategy and management, 14(3), 2021
5. Harvey, J. B. "The Abilene paradox: the management of agreement". Organizational Dynamics. 3: 63–80. doi:10.1016/0090-2616(74)90005-9, 1974.
6. Lucas, S., The Art of Public Speaking, 13e, Student Edition, McGraw Hill, 2020.

GLOBAL DISRUPTIONS AND THEIR IMPACT ON INTERNATIONAL LOGISTICS

Georgiana Surdu[1]
Valeriu Potecea[2]
Gheorghe Caraiani[3]

Abstract

There have always been delays in international transport, losses and disruptions to logistics chains, but the 2020-2026 period has put great pressure on transport and logistics companies, activating force majeure mechanisms more and more often.

From COVID-19 pandemic to the war in Ukraine, the Suez Canal incident, the Panama Canal water shortage, to the Gulf conflict, all these disruptions have led to increased transport costs and insurance premiums and ultimately, to higher prices for products traded globally.

This article aims to explore the effects of these crises on international logistics, highlighting the economic losses suffered through increased costs and increased delivery times. At the same time, we want to identify some possible solutions or alternatives to these critical problems in international transport and goods supply.

Key words: international logistics, trade, supply chain, transport systems

JEL Classification: F14, F62, R40, R41, E32

Discussion

Carrying out international trade transactions is a complex process, characterized by a succession of interdependent stages — production, processing, packaging, transport, logistics, storage, lotting, marketing and use — which never proceed in a linear manner. However, this mechanism can be deeply disrupted by exogenous factors, as demonstrated by the two major crises of the last five years: the Covid-19 pandemic and the military conflict in Ukraine. In parallel, secondary crises have also occurred, less visible to the general public, either because of their relatively low impact or because of the way they were covered in the media. The complexity of the operational chain varies depending on the capacities and quality of the actors involved — producers, intermediaries, traders — as well

[1] Lecturer, PhD, School of International Business, Romanian-American University, e-mail: georgiana.surdu@rau.ro, corresponding author
[2] Professor, PhD, School of International Business, Romanian-American University, email: valeriu.potecea@rau.ro
[3] Professor, PhD, School of International Business, Romanian-American University, email: georgecaraiani@rdslink.ro

as the existence of their own logistical resources. These secondary crises include the container crisis, the blockade of the Suez Canal, the semiconductor crisis and the energy crisis. However, the most significant recent development is the crisis of the development model based on internationalization, triggered by the change of the American administration.

Internationalization is not just a strategic aspiration, but a concrete alternative to carrying out activities exclusively on a national level. In this context, the behavior of the actors involved must be based on proactivity, an offensive attitude, continuous adaptation and systematic monitoring of results. The analysis of internationalization processes takes on new valences in the conditions of increasingly frequent paradigm shifts, and ignoring these transformations becomes impossible for decision-makers of organizations active in the global economy.

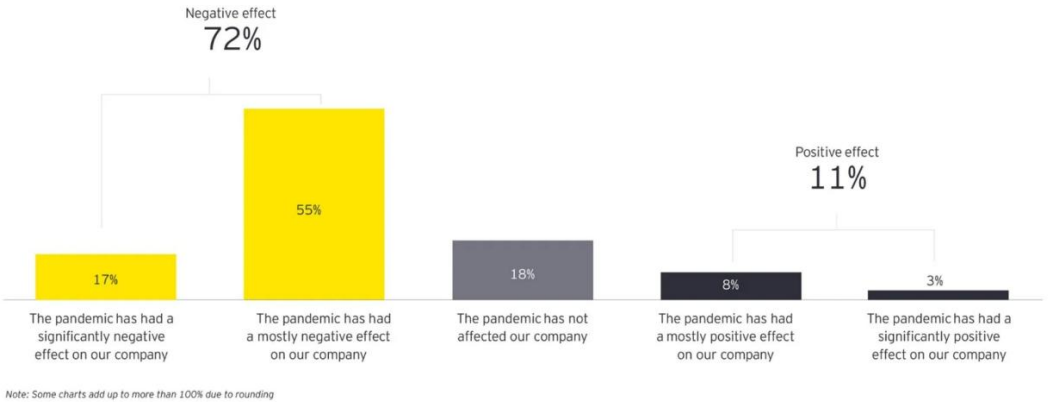
The new international economic framework, until recently marked by a dichotomous structure — between the temptation of emerging protectionism and the challenges generated by the consolidation of the quaternary sector — exposes economic actors to unprecedented pressures, which require the development of adaptation mechanisms similar to organizational "antibodies".

Achieving performance in cross-border business requires a rigorous decision-making process. To capitalize on the opportunities offered by foreign markets, companies must adopt coherent strategies for entering international markets, identify effective ways to reach local consumers, develop flexible supply chains, and choose organizational structures that maximize the benefits of international expansion. These decisions, based on the regulatory and technical framework of the target markets, can lead to the emergence of new organizational architectures, the adaptation of existing ones, or the formation of strategic partnerships. Entering the global arena requires a thorough understanding of the determinants of the international business environment: economic factors (including the dynamics of the balance of economic and trade forces, trade regionalism, foreign direct investment trends, and access to resources), demographic and cultural factors, technological factors (especially the role of innovation, digitalization, and technology transfer), legal and institutional factors.

The challenges generated by the multipolar of the global trading system, the intensification of competition from actors that efficiently exploit the advantages of economies of scale and diversification, as well as the transition to an economic model based on knowledge, sustainability and human capital development, force organizations that want to remain competitive to adopt behaviors adapted to target markets and explore new ways of approaching internationalization.

The COVID-19 pandemic represented a global disruption across trade, economy, health businesses and societies like few others in the past 100 years. In a EY survey from 2023, only 2% of companies who responded to the survey said they were fully prepared for the

pandemic. Serious disruptions affected 57%, with 72% reporting a negative effect (17% reported a significant negative effect, and 55% mostly negative).



Source: EY report- How COVID-19 impacted supply chains and what comes next, 2023

The same survey shows that COVID-19 accelerated many preexisting trends, and supply chain was no exception, 45% of supply chains are expected to be mostly autonomous (e.g., robots in warehouses and stores, driverless forklifts and trucks, delivery drones and fully automated planning).

But simply utilizing digital technologies does not mean an autonomous supply chain — it also needs connected supply chain technologies across planning, procurement, manufacturing and logistics that work beyond the organization.

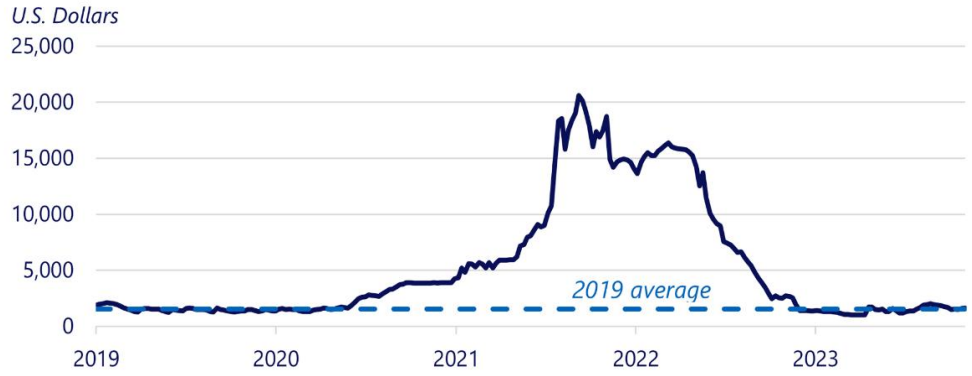
The implementation of artificial intelligence in the supply chain must be carried out in a strategic manner, considering not only the potential to increase operational efficiency and stimulate innovation, but also the technological and organizational vulnerabilities specific to each process or department. Such an approach allows for a balanced assessment of benefits and risks, facilitating the sustainable integration of AI-based solutions into the operational architecture of the enterprise. In the context of an increasingly volatile business climate, the redefinition of the foundations of competitiveness and the adoption of integrated approaches to production and marketing processes, supplier selection is a critical element for the efficient functioning of supply chains. Each product involves a specific set of benefits and risks in the supplier - customer relationship, which gives the decision-making process considerable complexity. In evaluating a supplier, customers typically consider variables such as price, quality, punctuality of deliveries, payment terms, the level of necessary investments and the technical capabilities of the supplier. Given the inherent difficulty of this process, the integration of artificial intelligence (AI)-based solutions can significantly contribute to optimizing and objectifying supplier selection, by increasing the accuracy of assessments and reducing decision-making uncertainties.

Beginning with February 2020, many countries announced travel restrictions to mitigate transmission of COVID-19, and passenger travel and freight were severely impacted.

To protect their staff's health, many companies have introduced new protocols on social distancing at warehouses, disinfecting work areas, or giving staff unlimited unpaid time off, all these measures had a massive financial impact on production and logistics.

Shipping container leasing rates have increased by as much as +300 and higher in the first six months of 2020, coupled with global price increases of many commodities and raw materials, as well as shipping prices worldwide.

Figure 1. Spot shipping prices from China to U.S. West Coast ports



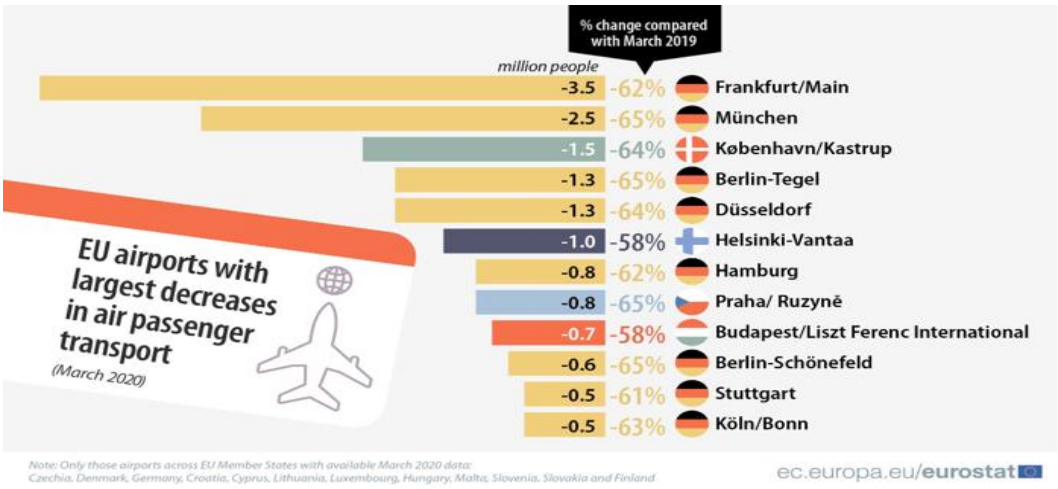
Council of Economic Advisers
Source: Freightos, Bloomberg, CEA calculations.
Note: Uses nominal dollars.
As of November 21, 2023 at 11:21 p.m.

Rates that were once 1.300 USD increased to 15.000 USD to over 20.000 USD/container on the spot market. Global manufacturing, especially in Asia, faced a huge demand that it wasn't equipped to ship all at once.

Also, with lockdown and global restrictions, millions of empty containers were stuck in the wrong regions, this created an artificial scarcity in the market. The UN Conference on Trade and Development (UNCTAD) calculated that the surge in container freight rates alone added 1,5% to global consumer price inflation.

The bubble burst in 2022 when pandemic restrictions were lifted, and simultaneously, the influx of new container ships ordered during the boom began to hit the water, creating an oversupply.

The immediate consequence of COVID-19 restrictions was a severe contraction in transportation capacity across all means of transportation. Although air transport had a severe drop in passengers transport, after the initial shock companies changed the business model and converted passenger planes into temporary freighters.



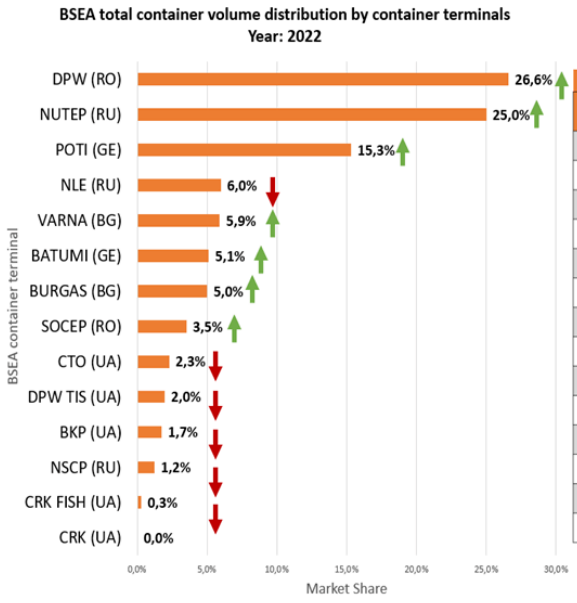
Air travel experienced the most severe contraction, with global passenger volumes dropping over 60% initially. The multi-billion-dollar losses triggered layoffs, airline restructurings and heavy debt accumulation.

While freight rates for companies have largely normalized from their pandemic spikes, the actual cost of operating a freight network remains permanently higher due to structural changes.

Also, the pandemic triggered early retirements and mass burnout among truck drivers and mariners. To attract and retain talent, companies had to raise wages and improve benefits.

Shortly after the logistics and business world breathed a sigh of relief that we had reached the end of the pandemic and could resume some of our old business practices, the war in Ukraine has triggered the most significant restructuring of European and global logistics since the end of the Cold War. What began as a shock has evolved into a "new normal" characterized by permanent route changes, structural labor shortages, and a massive shift in infrastructure investment towards Eastern Europe.

Ukraine has successfully bypassed the defunct "Black Sea Grain Initiative" by using its own corridor hugging the coastlines of Romania and Bulgaria, but the shipping tariffs across the region remain significantly higher than pre-war and insurance premiums are volatile. At its peak in 2023, Constanta port hit a record 92,5 million tonnes of total cargo, with Ukrainian grain accounting for over 14 million tonnes [1].



Total container turnover (Laden + Empty)			
BSEA container terminals	Year: 2022	Year: 2021	Change p.p.
DPW (RO)	26,6%	18,1%	+8,5 p.p.
NUTEP (RU)	25,0%	17,6%	+7,4 p.p.
POTI (GE)	15,3%	9,8%	+5,6 p.p.
BATUMI (GE)	5,1%	3,0%	+2,1 p.p.
SOCEP (RO)	3,5%	1,6%	+1,9 p.p.
VARNA (BG)	5,9%	4,3%	+1,7 p.p.
BURGAS (BG)	5,0%	3,6%	+1,4 p.p.
CRK (UA)	0,0%	0,0%	0,0 p.p.
NSCP (RU)	1,2%	2,3%	-1,0 p.p.
NLE (RU)	6,0%	7,0%	-1,1 p.p.
CRK FISH (UA)	0,3%	3,6%	-3,3 p.p.
DPW TIS (UA)	2,0%	7,7%	-5,7 p.p.
BKP (UA)	1,7%	8,9%	-7,1 p.p.
CTO (UA)	2,3%	12,6%	-10,3 p.p.

Source: Informall Business Group

It is noteworthy that Constanta took first place by total container turnover among the Black Sea terminals, handling 26.6% of the total regional container traffic in 2022. This achievement is an indication of the increasing significance of the Port of Constanta as a major hub for container shipping in the region and beyond.

Although road transport increased by over 40% at borders with Poland and Romania, it could not immediately take over the loads from the railway transport, and there it proved to be a great challenge because the gauges are different and significant time was lost with the transshipment of the loads, which also translates into lost money [2].

Before the conflict, the New Silk Road rail network through Russia and Belarus was a booming alternative to ocean freight for China-Europe trade. But after the first sanctions package, European freight forwarders largely abandoned the trans-Russian rail links to avoid sanctions and ethical liabilities.

Also, the closure of Russian airspace to “unfriendly” nations has permanently altered the economics of air cargo between Europe and Asia, rerouting of flights meant 3-4 hours lost, which translated into fuel consumption up to 20%.

Longer flights mean aircraft must carry more fuel, which directly reduces the maximum allowable weight for commercial cargo. This restriction reduced by approximately 10% to 20% of air freight capacity on critical Eurasian lanes, driving up cargo rates globally.

Cargo shifted heavily toward road freight causing severe bottlenecks at the Ukrainian-Polish and Ukrainian - Romanian borders, with trucks occasionally facing multi-week wait times because of customs procedures.

In 2026, the logistics situation remains highly fluid. Ongoing naval activity and mining the Black Sea have driven up maritime insurance costs to prohibitive levels, dampening commercial shipping traffic to Romanian and Bulgarian ports.

The Danube River is not a reliable backup route due to water level volatility; the weather fluctuated between flooding and very high temperatures that reduced the depth.

Currently, member states along the eastern border are experiencing higher inflation and slower GDP growth. Because Eastern European manufacturing and logistics clusters are more energy intensive and dependent on old supply chains, the soaring costs of fuel, labor and warehouse utilities are severely influencing the profit margins of logistics providers.

According to a policy document released by the European Commission (Communication on the Eastern External Border, 2026), we can see a 75% to 80% collapse in rail freight volumes previously tied to Russian transit.

Baltic ports reported reduced volumes of freight because traditionally they relied on Russian and Belarusian cargo (30%-40% of all cargo). To survive, Baltic logistics had to pivot and focus more on Western Europe and Scandinavia. Currently, they are working on Rail Baltica, a massive railway project designed to connect the Baltics to Poland and Central Europe.

Also, with Ukrainian air space closed and neighboring regions impacted by military operations, drone incursions and missile defensive risks, consolidated the position of some airports such as Leipzig, Liege or Budapest.

Russia has heavily modernized its own air freight infrastructure to survive sanctions. Has integrated air cargo hubs with rail and road networks to create intermodal corridors toward Asia.

Inside Ukraine, the financial toll is immense. Upwards of 25.000 km of roads, hundreds of bridges, and key rail hubs have been damaged or destroyed. According to United Nations (2026), Ukraine would need 588 billion USD for reconstruction and recovery overall, and 24% should be dedicated to building new transport infrastructure.

In another part of the world, the Panama Canal is slowly recovering from a two-year drought that crippled global trade routes. The canal operates using fresh water from Gatun Lake, and each ship transit flushes approximately 50 million gallons of water into the ocean.

In normal climate conditions, the canal will be transited by 36-38 ships, but during 2023-2025 the situation changed completely, only 18-22 ships/day could transit the canal. Also, ships were forced to carry less cargo to reduce draft, making every ship less efficient.

At the peak of the crisis, over 160 ships were queued at once, with some waiting up to three weeks to cross the canal.

Many bulk carriers and LNG tankers abandoned the canal entirely, opting for 10-14 days longer journey around Cape Horn or through the Suez Canal. Shipping companies began

"bidding" for the few available slots, one company paid a record of 4 million USD just for the right to skip the line (on top of the standard 1 million USD transit fee) [3].

The ACP (Suez Canal Authority) estimated a revenue loss of nearly 800 million USD to 1 billion USD for the 2024 fiscal year alone due to fewer transits. Although now the Panama Canal is operating at full capacity, the ACP is investing 1,6 billion USD into a new dam project on the Rio Indio to ensure this doesn't happen again when the next dry cycle hits.

To economically incentivize water efficiency and fund infrastructure, the ACP levies a "freshwater fee' on transiting vessels, which scales dynamically based on the real time water levels of Gatun Lake.

Meanwhile, in a recent announcement [4], the Panama Canal Authority has told ship agents, owners and operators that it will reduce the maximum authorized draught at its neopanamax locks to 14.94 m, in tropical fresh water from July 24. A further reduction to 14.78 m will follow on August 15.

This is not a severe restriction like the one during the 2023-2024 drought, when daily booking slots were slashed and many operators were forced to reroute. But it is a clear signal that the canal is again moving into defensive water management before the next dry season.

Another solution that has been tested is to use the Panama Canal Railway when draft limits drop. Mega-ships can offload a part of their cargo on one side, transit the canal lighter, and reload the containers via rail on the other side. Of course, this implies longer time with transshipments and more costly operations.

The crisis caused by the obstruction of the Suez Canal by the ship Ever Given for 6 days in March 2021 (23-29) showed the vulnerability of dependence on a single route and mode of transport. Of course, alternative options exist, but they are longer and more expensive and require reorientation with other types of transport, including combined transportation.

The ship was travelling from Tanjung Pelepas, Malaysia, to the Port of Rotterdam, Netherlands, and the crew being entirely of made of Indian nationals (23 members). Is owned by a Japanese company and operated by the Taiwanese company Evergreen Marine.

Ever Given can hold 20,000 containers and is 1,300 feet (400 meters) long and 193 feet (59 meters) wide. (Empire State Building is shorter - 1,250 feet or 382 meters).

Around 12% of global trade or 30% of international containers pass through the Suez Canal, and 30% of the world's container traffic was delayed. The delay also meant that intermediate products for production were missing, and other products could no longer be sold or could only be sold at a discount

About 400 ships were affected by the accident. Nearly 19,000 ships passed through the canal during 2020, for an average of 51.5 per day, according to the Suez Canal Authority.

Lloyd's List estimates that more than $9 billion worth of goods passes through the 120-mile waterway each day, translating to around $400 million per hour. The direct costs amount to at least 1 billion EUR in total. Allianz estimated the losses triggered by the blockade of the Suez Canal at up to 10 billion USD per week [5].

Unfortunately, the accident hit maritime transport at a time of strained transport chains. In the short term, as an alternative, one could have tried to switch to container trains traveling from China to Europe via the Eurasian Land Bridge. But their capacities were limited.

The existing railway connections of the Eurasian land bridge run through Russia. China has recognized the strategic dependence and is trying to develop alternative solutions, like the route south of Russia via Iran and Turkey as part of the Belt and Road Initiative.

Air freight – certainly an alternative for high-value goods – is also very busy. Even before the Ever-Given disaster, there were significant delays. Due to the current sanctions against Russia, the country has closed its airspace to airlines from the EU and many other countries. This shows how vulnerable individual modes of transport are and how important it is for international supply chains to have alternatives.

Currently, the infrastructure and operational integrity of the Suez Canal are facing multiple crises. While the infrastructure has seen technical upgrades, its utility as a global maritime artery is severely compromised by a combination of regional conflict, geographical bottlenecks and vulnerabilities in the digital and physical networks that support it.

After the Ever-Given incident, the Egyptian authorities aimed at widening and deepening the narrowest parts of the canal to increase navigational safety by a reported 28%. Especially that undersea fiber-optic cables passing through these shallow waters are highly vulnerable to being dragged by ships' anchors or targeted by hybrid warfare or sabotage.

But the obstruction of the Suez Canal was not to be the most important event to affect the region, the conflict in Gaza has triggered a massive disruption in global logistics, primarily by turning the Red Sea, especially Babel-Mandeb Strait and the Suez Canal into a high-risk zone.

Because of this, ships were circumnavigating the entire continent of Africa, and this added roughly 3.500 to 4.000 miles and 10 to 15 days to the journey.

Also, because ships spent two weeks longer at sea, they couldn't turn around and start new voyages as quickly. That detour absorbed 5% to 7% of global container fleet capacity, tightening shipping availability worldwide [6].

Standard maritime insurance policies exclude war risk. Obtaining a policy that endorses war risk for regional transit has become very expensive, often costing between 150.000 USD and 500.000 USD per single voyage, or 0,5% to 1 % of the total cargo value.

Spot rates for containers on the Asia-to-Europe Lane have seen spikes of 30-40%, with some specific surcharges reaching up to 4.000 USD per container. Some insurers have withdrawn coverage entirely for the Persian Gulf and Red Sea [7].

The prolonged conflict has made clear that the era of cheap, highly predictable global shipping is over and companies must adapt to the new realities.

Companies with time-sensitive goods shifted to air freight, but this caused air cargo rates on certain international routes to surge by as much as 70%. Major transit hubs like Dubai and Amman have faced congestion because of airspace closures and safety protocols.

And again, when the logistics world believed that the end of the conflict in the Gaza Strip would bring peace and a return to international trade without restrictions and at affordable costs, the recent conflict in the Gulf and the blockade of the Strait of Hormuz completely disrupted international trade, especially industries related to the petrochemical and energy sectors.

The Strait of Hormuz is called the world's most important oil chokepoint, but now the region is experiencing a severe escalation in conflict, creating the largest disruption to global energy and logistics since the 1970's.

Daily transits have plummeted from a normal average of 60 ships per day to fewer than 3 on some days. Limited exemptions have been granted to vessels from countries like India, China, and Turkey.

The disruption of this single point of failure has sent shockwaves through the global economy. Crude oil (Brent) surged past 100-120 USD per barrel, and the strait carries 21% of the world's oil supply and 25% of global LNG [8].

The Middle East is a primary exporter of fertilizers as well; the blockade has caused a spike in global agricultural input costs. Also, high concentration of refined aluminum and petcoke originate in the Gulf, and because of this, many industries in Asia and Europe are reporting "force majeure" due to the instability and scarcity of raw materials.

War-risk insurance for any vessel entering the Arabian Peninsula has multiplied by 12-15 times, making the voyages economically unviable even if physical passage were possible.

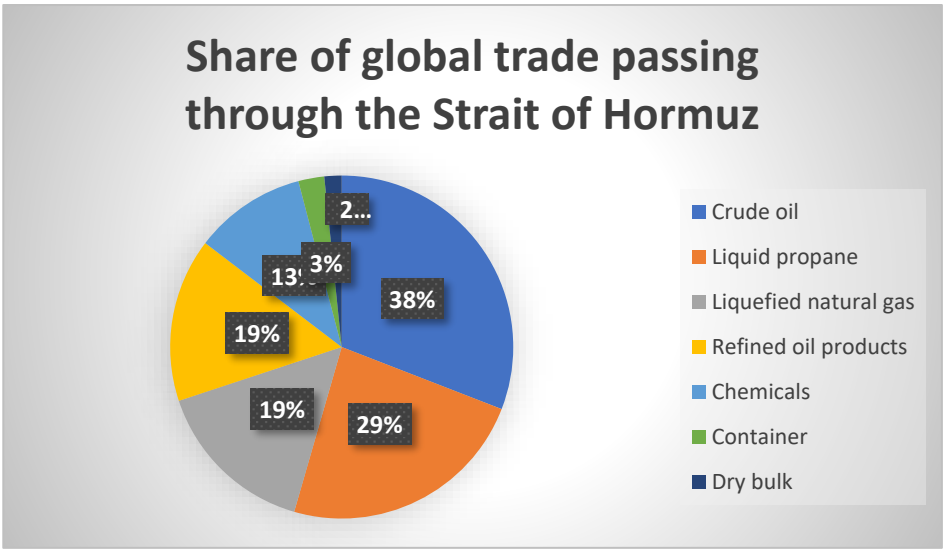
With both the Strait of Hormuz restricted and the Suez Canal/Red Sea route still considered high-risk due to Houthi activity, ships are forced into the Cape of Good Hope detour. Major hubs like Jebel Ali and Dammam are effectively cut off from sea-bound container traffic, leading to a massive backlog of goods and canceled stops across global schedules.

The Houthi lunched their maritime campaign in November 2023, claiming to target Israeli linked vessels, but soon after included US and British vessels, and over time vessels with no discernible ties to Israel or its allies were attacked.

These almost 200 attacks had an important economic impact, companies rerouted vessels to avoid attacks, but this led to increases in fuel consumption, and longer transit time.

For Arab and Middle East nations, the impact was severe. Reduced market access and logistics bottlenecks caused a projected 104 billion USD drop in exports over the duration of the crisis, alongside a 20 billion USD increase in the cost of their own imports.

This shift towards the Cape of Good Hope increased port activity, bunkering and maritime services for South African ports, Namibia's Walvis Bay and Mauritius. However, the unexpected congestion severely strained local infrastructure, forcing a massive push toward digitizing customs and upgrading loading/unloading infrastructure.



Source: UN Trade and Development - statistics based on average lows during the week before the military escalation

The ongoing conflict impacting the Strait of Hormuz choked off vital products from the Gulf region, like fertilizers. Countries like Sudan, Somalia, Kenya are heavily impacted.

Sudan already was under a lot of pressure economically and logistically because of their internal unrest, and Port Sudan became a contested, bottlenecked lifeline for the country. The war disrupted the transit of humanitarian aid, fuel and vital food into neighbors like Chad and the Central African Republic.

On top of these major disruptions that took place between 2020-2026, cyber-attacks against freight forwarders, third-party logistics providers, and ocean carriers surged by a staggering 965% between 2021 and 2025.

According to Supply Chain Exchange (2026), state-sponsored actors launched coordinated digital assaults alongside physical harassment—such as widespread GPS jamming in the Baltic Sea. These actions blinded maritime navigation systems and put 15% of global cargo shipping at risk.

According to Everstream Analytics, cyberattacks on ports and logistics infrastructure may seem unpredictable, but their cascading effects on supply chains follow recognizable patterns. Companies can mitigate this risk by implementing advanced supply chain risk

monitoring platforms that can work with thousands of risk variables across global logistics networks, providing companies with a key first-mover advantage.

The same publication shows that global infrastructure requires $106 trillion of investment through 2040, with $36 trillion needed for logistics and transport alone. Port disruptions from infrastructure maintenance and systems outages are trending upward.

Overall, between 2020 and 2026, while logistics disruptions were global phenomena, Asia-Pacific and Europe were the most affected by supply chain and transport shocks, but for different reasons.

Asia-Pacific was affected because of manufacturing lockdown and bottleneck, container disparities, as containers became stuck in North America and European ports, and extreme weather impacting important hubs in China, Taiwan and India.

Europe was affected by a severe geopolitical situation and energy-related crisis that impacted logistics providers as well. Also, Europe is the most geographically exposed transit destination.

Potential approaches and conclusions

The era of predictable global trade is over, and to survive and thrive in these challenging times, logistic companies must shift from reactive crisis management to proactive resilience.

Supply chains were already structurally sensitive due to post pandemic reconfigurations, and proved to be highly vulnerable to geopolitical shocks, such as recounting around conflicts.

Shippers and logistics providers are spending significantly more money on redundancy, regionalized networks, and technology simply to achieve the same level of stability they had before the pandemic.

One of the approaches for crisis mitigation could be the **new technological wave**, that can act as a buffer and absorb the shock of a crisis by decoupling productivity from physical presence. Solutions like Digital Twins, where companies create a virtual mirror of their entire supply chain and run "what if" simulations to find alternative routes before the crisis hits, Autonomous Last-Mile Deliveries using drones and small sidewalk robots, or Automated Warehousing systems, all can become long term solutions supervised by people.

Carriers and shippers could implement real time AI and predictive analytics to reroute vessels long before they reach active conflict zones or congested hubs.

But as we said earlier, cyberattacks have increased in recent years and modern facilities, based on operational technology are more exposed to this risk. Hackers exploit the trusted digital portals shared between shippers, external contractors and carriers to bypass firewalls entirely.

Multimodal transport should be used in a more agile version. For example, the North American Land Bridge has become a vital transport artery. Ships coming from Asia bypass the Panama Canal entirely discharging their cargo at US West Coast ports. The containers are immediately loaded onto intermodal rail or long-haul trucks to cross to the Gulf area or East Coast destinations.

Also, the **Just-in Case logistics** has seen a massive resurgence lately. After decades of Just-in Time, efficiency being the gold standard, global volatility has taught us that being "lean" can sometimes mean being fragile. Maintaining higher inventory for critical components and raw materials can act as a shock absorber against sudden demand spikes, prices increase or transport delays. Of course, this approach works for short periods, if you have cash, and if those components or raw materials do not expire quickly and do not lose value.

Another potential solution identified by us would be **more investments in strategic infrastructure,** having alternative routes such as the Middle Corridor (combining rail and ferry across the Caspian and Black Seas), or expanding deep-water ports outside the immediate chokepoint zones (like ports in Oman or the UAE facing the Arabian Sea).

For example, in early 2026, the Port of Constanta moved to take over the Giurgiulesti Port in Republic of Moldova, a move aimed at streamlining the entire Danube-Black Sea corridor.

This is a strategic move for Eastern European logistics, as Giurgiulesti is uniquely equipped with both narrow and wide-gauge railway lines, and now Constanta owns a direct translator node, and can offer solutions for consolidated cargo.

A recent initiative, lunched at the industrial summit held in Antwerp in 2026, talks about **"Made in Europe".** At its core, it introduces binding "European preference" and low-carbon requirements for public procurement and subsidies in strategic sectors, and to decrease dependencies on foreign powers like China and the U.S.

Furthermore, "Made in Europe" framework directly targets logistical and supply chain crises by replacing long, fragile global shipping routes with regionalized, "bulletproof" logistics network infrastructure. By forcing the localization of key components (like requiring 70% of electric vehicle parts or solar panels to be made in the EU), the policy fundamentally reduces Europe's exposure to maritime chokepoints.

This shifts logistics from high-risk, long-haul freight to more agile, cross-border European logistics. Transit times will drop from months to days, reducing the amount of capital tied up in inventory in transit.

Although on paper seems very good, it won't happen overnight. Logistics providers and manufacturers would have to re-engineer and optimize supply chains, adjust to strict new compliance and invest in low-carbon vehicles and technologies.

In our opinion, negotiation is a determining factor in supply chain management, constituting an essential competence with a direct impact on operational performance and long-term

strategic success. It influences critical decisions such as supplier selection, establishing contractual conditions, determining prices, defining guarantees, allocating responsibilities and dispute resolution mechanisms, thus becoming a central tool in aligning the objectives of the parties involved and in mitigating risks in a global environment characterized by complexity and volatility.

Negotiation activity is a fundamental strategic tool, capable of amplifying both the reactivity and efficiency of the supply chain. Strategic negotiation allows organizations to anticipate and effectively manage challenges such as supply disruptions, inflation, price volatility, demand fluctuations or quality issues, facilitating the adoption of precise and agile actions without compromising relationships with trading partners. Beyond technological advances, cultural intelligence has become an essential element of modern supply chain negotiations. Relational factors such as trust, commitment and reciprocity also shape the dynamics of negotiations. The importance of maintaining a balance between supply chain performance and strategic planning in achieving competitive advantage is critical. The integration of supply chain processes and strategic adaptability contributes decisively to achieving competitive advantage by improving internal collaboration, strengthening relationships with external partners and increasing resilience to changes and disruptions in the global environment. Strategic planning in supply chain management, increasingly important in the context of its complexity and globalization, contributes to efficiency, resilience and long-term competitive advantage.

With the increasing complexity and global footprint of supply chains, broader risks are emerging, which can be identified and managed in a differentiated manner. Reducing the negative effects generated by the materialization of risks depends on the application of advanced procurement strategies, used by professionals in the field both in decision-making processes with a high degree of rationality and in situations characterized by significant irrational components. Risk mitigation strategies effectively contribute to reducing the exposure of organizations to supply chain-specific risks.

A universal mechanism applicable to all companies to ensure, at any time, a minimum level of risk exposure cannot exist. Flexible approaches are needed, adapted to the operational context and the particularities of each supply chain.

The response of companies to the plethora of systemic shocks in recent years (coronavirus pandemic, energy crises, geopolitical and military tensions, protectionist trade policies, etc.), have imposed the need to adapt, by implementing nearshoring or friendshoring strategies. These supply chain strategies, designed to increase resilience and reduce risk in response to global disruptions, aim to replace vulnerable, remote supply chains with more secure and reliable networks. Companies' concerns about the digitalization and sustainability of supply chains are key elements in responding to current and future challenges.

References

1. Ernst Iulian, *Romania's Constanta port posts new traffic record in second year of war in Ukraine,* January 2024, Romania Insider
2. European Commission, Directorate for Mobility and Transport, *Solidarity Lanes: Latest figures- December 2025*, February 2nd, 2026
3. Tse Ivy, Panama Canal drought: impact on global shipping, July 28th, 2025, Freight Amigo Blog
4. Malheiros Gabriel, Panama Canal tightens draught limits again, DatamarNews, July 2026
5. Subran Ludovic, The Suez Canal ship is not the only thing clogging global trade, March 26th, 2021, Allianz Trade
6. Suaid Tiago, Red Sea Shipping Crisis: Impact on Your Supply Chain, Suaid Global, 2026
7. Batool Kate, Supply Chain Disruption 2025- Red Sea, Panama and Tariff Risks, March 9th, 2026, MacMillan Supply Chain Group
8. Dunn Gibson, *Commercial and supply chain implications of the Gulf conflict: shipping, contracts and insurance*, March 4th, 2026

Bibliography

1. Trishnakhi Parashar, *Hormuz under pressure: Energy supply chains and maritime logistics at risk,* March 16th, 2026, Bloomsbury Intelligence and Security Institute
2. UN Trade and Development statistics
3. Informall Business Group statistics
4. RiskIntelligence, How the Russia-Ukraine war reshapes Baltic Sea risk, May 2026
5. Harapko Sean , How COVID-19 impacted supply chains and what comes next, EY, 2023
6. Albers, S., Brandhagen, V., & Wens Veen, J., The impact of COVID-19 on global air cargo operations, 2021
7. Everstream Analytics, Annual Supply Chain Risk Report 2026
8. Sayed Asif Mahmud, Ukraine; $588 billion recovery cost over the next 10 years, United Nations, 2026
9. Victoria Sainz, The Red Sea Shipping Crisis: Houthi Attacks and Global Trade Disruption, Atlas Institute, 2025

DIGITALIZATION STRUCTURALLY CHANGES THE LABOUR MARKET: A COMPARATIVE ANALYSIS IN EU COUNTRIES

Alexandru TĂBUȘCĂ[1]

Alexandra HOSSZU[2]

Mihai Alexandru BOTEZATU[3]

Andrei LUCHICI[4]

Silvia TĂBUȘCĂ[5]

Alexandru ENĂCEANU[6]

Dragoș-Paul POP[7]

Abstract

The process of automation, implementation, and expansion of information and communication technologies (ICT) in EU countries has had a strong impact on the labour market, which has undergone significant transformation, as advanced technologies both create and eliminate numerous jobs. Consequently, the number, structure, and quality of jobs available on the labour market have changed considerably, together with the skills and competencies required to fill them. At the same time, the education and vocational training systems must adapt to these new competency requirements, which increasingly emphasize specific human and social skills.

Under these circumstances, this study analyses the expansion of the digitalization process in EU countries during the period 2010-2024 by examining several key indicators: GDP per capita, employment rate, unemployment rate, and the number of employed ICT specialists. We subsequently analysed the evolution of the online labour demand market on a quarterly basis during the period 2019-2025 in order to observe changes in the occupational distribution of labour demand.

The study reveals different levels of digitalization and automation across EU countries by the end of 2024, as well as different patterns in the evolution of occupational labour demand during the analysed period. The conclusions of the analysis may assist decision-makers in

[1] PhD Associate Professor, Romanian-American University, Romania, alex.tabusca@rau.ro; corresponding author
[2] PhD Associate Teaching Staff, University of Bucharest, Romania; alexandra.hosszu@sas.unibuc.ro
[3] PhD Professor, Romanian-American University, Romania, mihai.botezatu@rau.ro
[4] PhD, Lecturer, Center for Research in AI, Romania, andrei.luchici@rau.ro
[5] PhD, Lecturer, Center for Human Rights and Migration, cdom@rau.ro
[6] PhD, Lecturer, Romanian-American University, Romania, alexandru.enaceanu@rau.ro
[7] PhD, Assoc. Lecturer, Romanian-American University, Romania, dragos.paul.pop@rau.ro

EU countries in shaping policies aimed at stimulating adaptation and flexibility within higher education and vocational training systems, as well as investments in research and development and occupational health and safety activities.

Keywords: digitalization, digital skills, ICT specialists

JEL Classification: O1, O150, C12

1. Introduction

Digitalization and the expansion of information and communication technologies (ICT) across all areas of economic, social, and cultural life have become key objectives on the agendas of several international institutions, including the World Bank Group, the World Economic Forum, the International Labour Organization, the European Commission, the European Parliament, and the OECD. These institutions have supervised, regulated, monitored, and encouraged the so-called digital revolution.

The process of automation and the implementation and expansion of ICT in the economies and societies of EU Member States have been strongly supported by the European Commission, national governments, specialized institutions, research institutes, and academia, all of which have demonstrated the major impact of these technologies on the lives of European citizens.

The expansion of digitalization, the increasing use of robotics, and the gradual transition toward Artificial Intelligence (AI) have been continuously analysed by the OECD [1][2], monitored by the ILO [3][4], the European Commission [5][6][7], and the European Parliament [10]. These institutions have highlighted the risks associated with automation, robotics, and AI regarding the loss of traditional jobs, but especially the emergence of new requirements in terms of competencies and skills necessary for future employment opportunities.

Similarly, the World Economic Forum has repeatedly drawn attention to the future risks associated with job displacement caused by automation and computerization, as well as the resulting impact on employment and unemployment within modern societies [11][12].

These developments have profoundly affected labour markets. Advanced technologies simultaneously create and eliminate jobs. Employees increasingly face the disappearance of automated positions and substantial changes in the digital and communication skills required for their current occupations. At the same time, employers have vacancies requiring digital competencies ranging from basic to highly advanced levels, which necessitate either higher education qualifications or specialized training programmes.

As a result, the number, structure, and quality of jobs available on the labour market have changed significantly [13], together with the competencies and skills required to perform them, as well as the processes of lifelong learning and continuous adaptation [14][15].

In order to maintain equilibrium in labour markets, substantial efforts are being made to ensure that the workforce adapts to new technologies and is prepared to cope with the growing automation of activities. These efforts involve employers, employees, unemployed individuals, governments, public administrations, and local authorities, all of whom contribute through policies adapted to their specific contexts. Such measures are continuously required to address the opportunities and challenges generated by technological change.

In response to labour market requirements and their own operational needs, an increasing number of companies have adapted by organizing specialized ICT training programmes both for their own employees and for other interested workers. The Managing Director of the International Monetary Fund (IMF) has emphasized that the impact of digitalization on labour markets is substantially stronger in advanced economies (approximately 60%) than in developing economies (approximately 30%), which may inevitably increase global inequality [16].

2. Previous Literature in the Field

Concerned about the risk of job loss and uncertainty regarding future employment opportunities, both employees and employers have increasingly focused on understanding labour market transformations. Recent research has examined changes generated by the automation and computerization of entire work, learning, and decision-making processes, including the potential deepening of social inequalities and, conversely, the reduction of poverty among employed populations [17].

It is well known that labour market conditions can be assessed through rigorous indicators such as the employment rate, unemployment rate, GDP per capita, and the degree of automation and digitalization, often measured by the number of employed ICT specialists. Accordingly, we reviewed studies investigating the relationship between the digitalization of activities and services, progressive robotization, employment, unemployment, and economic development both within the European Union and beyond.

The business sector has increasingly requested studies capable of guiding organizations during a period characterized by the implementation of innovative and ICT-based technologies, which generate not only economic efficiency but also significant uncertainty regarding the content of emerging occupations and new job roles.

Several studies [18][19] have identified occupations likely to disappear as well as a growing range of new jobs increasingly demanded on the labour market. These positions are primarily related to software application development, big data analytics, cybersecurity, green energy engineering, and ICT specializations in healthcare, manufacturing, education, and social services.

Researchers have also analysed and synthesized the competency requirements associated with these emerging occupations, making them widely available through their studies [20][19][21][22][23][24].

Other scholars have investigated the correlation between economic development and the number (or percentage) of employed ICT specialists, as well as the direct impact of digitalization on employment rates, unemployment, and wage levels across countries [25][26][24][27][28][29][30]. Research by Bachman, within a study on 16 European countries between 2000-2017, [31] has shown that the effects of robotics are felt most strongly by workers performing predominantly manual and repetitive tasks and less intensely by workers engaged in cognitive activities. Furthermore, in less developed countries, employment has increased and unemployment caused by technological displacement has declined due to the creation of new jobs and the implementation of policies encouraging labour mobility among specialized workers.

A study conducted for the OECD Social [32], Employment and Migration programme examined 21 OECD countries and assessed the risk of job loss resulting from the extensive adoption of ICT technologies. The findings suggested that only 9% of jobs were highly automatable and therefore exposed to a substantial risk of total or partial elimination, whereas several traditional occupations identified in other studies have already disappeared or are currently declining [19].

This conclusion significantly reduced concerns regarding large-scale job losses caused by digitalization, robotization, and computerization. Moreover, the study demonstrated that this percentage varies among countries depending on their level of development, investment in research and innovation, ICT expenditure, educational attainment of ICT specialists, and overall social and technological progress.

A substantial body of research has also focused on the competencies required by new occupations strongly influenced by automation and computerization. The introduction of new technologies may lead to the disappearance or significant transformation of existing job tasks, while simultaneously generating concerns among employees and their families regarding income security, unemployment risks, and the need to adapt through acquiring new knowledge, competencies, and skills required by emerging working conditions [33][34][35][36].

3. Preliminary Data Analysis

Consistent with a large part of the literature reviewed, our analysis considered data on GDP per capita, employed ICT specialists, employment rate, and unemployment rate for the 27 EU Member States during the period 2010-2024. The data were obtained from the Eurostat database [75] and subsequently processed and synthesized by the authors.

It should be noted that EU Member States exhibit different levels of economic development. Consequently, the expansion and intensification of digitalization, automation, and

robotization processes differ substantially among countries, which may further widen existing development gaps.

An analysis of the GDP per capita (GDPpc) indicator for the 27 EU Member States, expressed in euro per capita (Table 1), reveals a continuous increase over the fifteen-year period under review. This reflects both economic growth and improvements in living standards throughout the European Union.

However, a closer examination shows that several countries started from very low GDP per capita levels in 2010, considerably below the EU average. Although these countries experienced significant growth rates, their GDP per capita remained relatively low compared with the EU average in 2024.

This is particularly evident in the cases of Bulgaria and Romania, whose GDP per capita increased from €7,060 and €8,050 respectively in 2010 to €11,300 and €13,130 in 2024. Although the percentage increases were substantial (approximately 60% and 63.1%, respectively), both countries remained well below the EU average of €33,550 in 2024.

A similar situation can be observed in Hungary, Latvia, Lithuania, and Poland, which, despite recording notable economic progress, also remained below the EU average by 2024. During the analysed period, these countries implemented intensive digitalization programmes supported by substantial ICT investments, which significantly contributed to economic growth, as demonstrated by previous research [37][38][39].

Conversely, several countries began the period, in 2010, with GDP per capita levels significantly above the EU average and continued to grow steadily while maintaining their advantageous position even in 2024. These include the highly developed EU economies of: Denmark, Germany, Ireland, Netherlands, Austria, Finland, Sweden, Belgium, France and Italy.

A special case is represented by Luxembourg, whose GDP per capita reached €103,430 in 2010 - approximately 3.6 times the EU average. Although it experienced slight fluctuations thereafter, Luxembourg maintained a GDP per capita level roughly three times higher than the EU average throughout the analysed period.

Country / Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
European Union-27	28,52	29,03	28,76	28,72	29,16	29,78	30,29	31,09	31,67	32,20	30,44	32,36	33,26	33,28	33,55
Belgium	39,42	39,67	39,51	39,44	39,96	40,31	40,59	41,03	41,61	42,40	40,19	42,51	43,96	44,12	44,30
Bulgaria	7,06	7,39	7,53	7,60	7,76	8,13	8,48	8,83	9,18	9,67	9,45	10,25	10,74	10,97	11,30
Czechia	17,77	18,12	17,97	17,97	18,37	19,27	19,76	20,76	21,32	22,05	20,98	21,83	21,91	21,68	21,91
Denmark	49,01	49,44	49,26	49,75	50,11	50,81	51,95	53,20	53,92	54,63	53,54	56,78	56,53	56,47	58,16
Germany	38,42	39,87	39,98	40,02	40,72	41,04	41,64	42,61	42,96	43,29	41,48	42,99	43,26	42,78	42,58
Estonia	15,38	16,59	17,26	17,63	18,28	18,65	19,19	20,27	20,97	21,65	20,96	22,44	22,43	21,21	21,02
Ireland	43,99	44,51	44,15	44,89	48,77	60,21	60,22	65,37	69,39	71,72	75,82	87,16	91,76	87,81	88,60

Greece	19,30	17,42	16,05	15,80	16,03	16,10	16,16	16,43	16,81	17,21	15,66	17,11	18,20	18,67	19,13
Spain	24,51	24,26	23,56	23,31	23,73	24,72	25,42	26,11	26,62	26,93	23,85	25,44	26,77	27,15	27,74
France	34,31	34,99	34,88	34,99	35,15	35,37	35,54	36,14	36,57	37,16	34,28	36,47	37,32	37,76	38,11
Croatia	11,44	11,47	11,25	11,27	11,26	11,60	12,10	12,63	13,12	13,87	12,84	14,56	15,64	16,06	16,71
Italy	30,44	30,55	29,51	28,92	28,91	29,21	29,63	30,16	30,47	30,68	28,10	30,76	32,31	32,56	32,81
Cyprus	23,89	23,39	22,28	20,83	20,49	21,14	22,41	23,50	24,69	25,79	24,63	27,03	28,44	28,67	29,19
Latvia	10,84	11,38	12,36	12,75	13,14	13,75	14,23	14,85	15,61	15,82	15,37	16,58	16,87	17,39	17,51
Lithuania	11,16	12,14	12,83	13,48	14,10	14,63	15,20	16,09	17,03	17,87	17,89	19,04	19,36	19,16	19,58
Luxembourg	103,43	102,11	101,44	102,01	102,24	102,53	104,92	104,02	103,64	104,31	102,19	107,57	104,10	101,45	100,88
Hungary	11,06	11,30	11,22	11,49	12,04	12,53	12,88	13,46	14,24	14,98	14,37	15,47	16,17	16,06	16,19
Malta	20,73	20,85	21,53	22,59	23,83	25,50	25,95	28,51	29,49	29,46	27,89	31,41	31,91	32,74	33,61
Netherlands	44,40	44,98	44,37	44,23	44,78	45,53	46,38	47,39	48,18	48,97	46,81	49,49	51,48	50,66	50,88
Austria	42,28	43,37	43,45	43,08	43,07	43,20	43,55	44,26	45,14	45,73	42,65	44,52	46,35	45,51	44,83
Poland	10,15	10,68	10,84	10,93	11,36	11,87	12,24	12,87	13,68	14,31	14,31	15,38	15,84	15,95	16,47
Portugal	19,44	19,11	18,41	18,33	18,56	18,92	19,35	20,02	20,62	21,15	19,36	20,39	21,69	22,02	22,23
Romania	8,05	8,46	8,66	8,71	9,10	9,43	9,76	10,62	11,33	11,83	11,46	12,19	12,73	13,03	13,13
Slovenia	19,92	20,01	19,39	19,21	19,72	20,17	20,77	21,83	22,72	23,33	22,23	24,04	24,66	25,05	25,38
Slovakia	14,10	14,54	14,75	14,83	15,22	16,00	16,28	16,73	17,38	17,76	17,27	18,32	18,35	18,75	19,13
Finland	41,66	42,46	41,62	41,02	40,65	40,70	41,64	42,91	43,36	43,91	42,74	43,80	44,01	43,43	43,04
Sweden	43,13	44,15	43,65	43,77	44,33	45,79	46,22	46,42	46,70	47,41	46,18	48,30	48,39	47,96	48,30

Tabel 1. DP per capita - Gross domestic product at market prices (euro per capita)
Source: Eurostat(2026), Database on Economic and Finance
(https://ec.europa.eu/eurostat/data/database)

A graphical representation of these data for 2024 can be seen in Fig. 1.

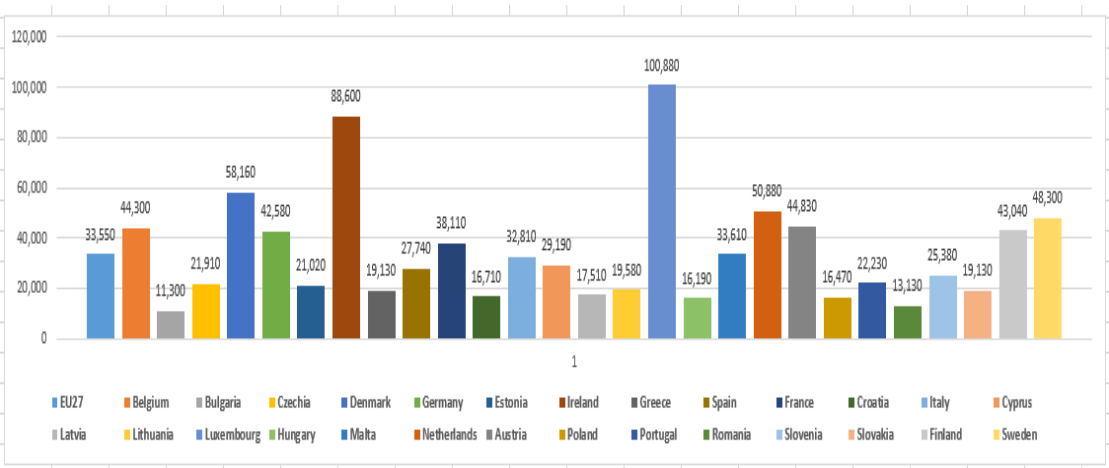


Fig.1 PIBL-Gross domestic product at market prices (euro per capita) in 2024

An analysis of the employment rate among the population aged 20-64 in EU countries during the period 2010-2024 shows that several less-developed Member States experienced substantial increases in employment alongside economic growth. Particularly significant increases were recorded in: Bulgaria, Estonia, Ireland, Latvia, Lithuania, Hungary, Malta, Poland and Romania. Employment growth in these countries ranged from approximately 19.8% to 30%, reaching nearly 37% in Malta.

This trend has also been confirmed by previous studies [40][41][42][43][44], which demonstrate that economic and social development generate new and diversified employment opportunities, thereby significantly increasing the employment rate of the working-age population.

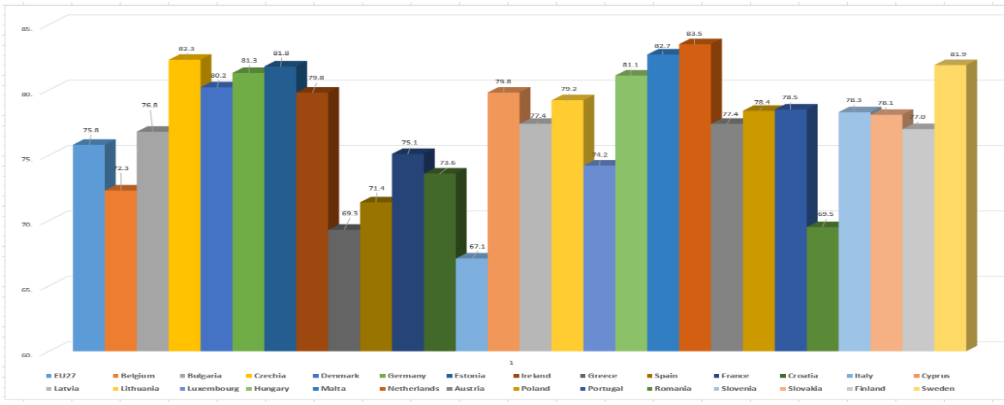


Fig 2. Total employment rate - From 20 to 64 years (Percentage of total population) in 2024

Similarly, unemployment rates across EU countries displayed substantial dynamics during the period 2010 - 2024.

Economic growth, reflected in increasing GDP per capita and rising employment rates, led to a considerable decline in unemployment in most European countries. The reductions observed generally ranged between 20% and 70%.

Nevertheless, a few countries recorded only limited decreases:

- Finland - decline of approximately 2-3%
- Sweden - decline of approximately 2-3%
- Austria - essentially unchanged

A particularly notable case is Luxembourg, where unemployment increased by approximately 45%, rising from 4.4% in 2010 to 6.4% in 2024.

These developments were influenced by the digitalization and automation of production, service, and work processes, which simultaneously eliminated certain jobs while creating new employment opportunities. In highly developed and highly digitalized economies, a slight increase in unemployment was observed as labour markets adjusted to these structural transformations [45][27][46].

The graphical representation of these values for 2024 can be seen in Fig. 3., below.

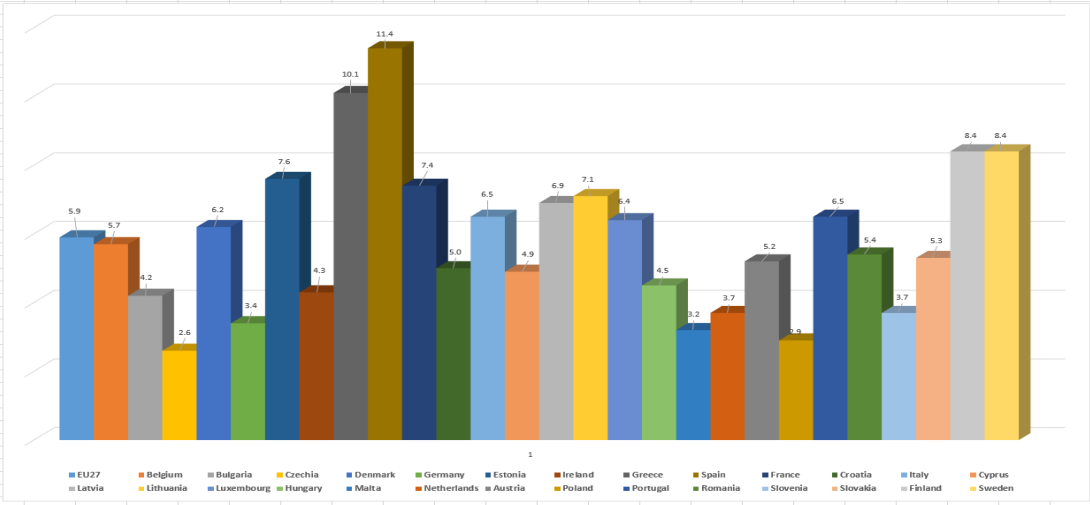


Fig. 3. Unemployment rate Total (Percentage of population in the labour force) in 2024

An analysis of the evolution of employed ICT specialists in EU countries between 2010 and 2024 reveals that only two countries experienced a decline:

- Czechia - approximately 3% decrease
- Greece - approximately 14% decrease

In all other EU countries, the number of ICT specialists increased significantly, demonstrating both the expansion and intensification of digitalization and automation across economic sectors.

For most countries, growth rates were broadly in line with the European average, ranging between 30% and 40%.
Particularly remarkable increases were recorded in:

- Estonia
- Netherlands
- Portugal

where growth exceeded 75%.
Even more striking increases were observed in:

- Croatia
- Lithuania

where the number of ICT specialists more than doubled.
These findings indicate that digital technologies and work-process automation were strongly supported in these countries and contributed significantly to economic growth. [37][47][48]

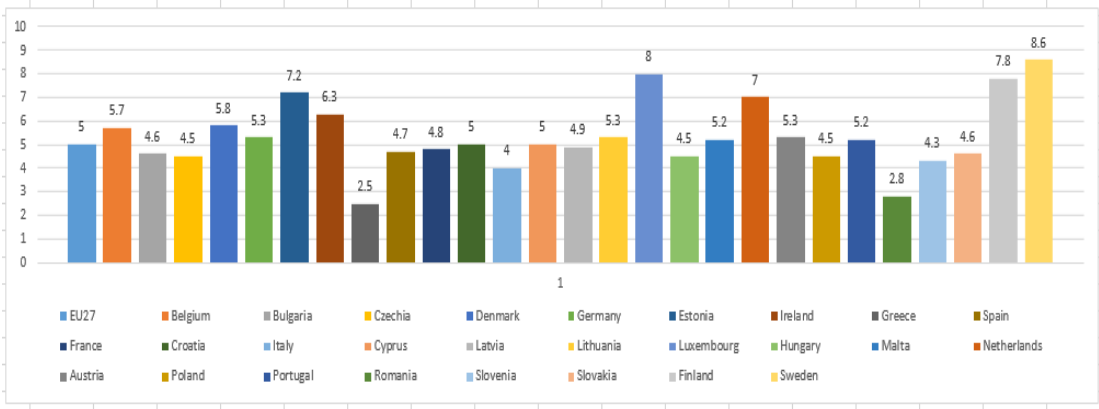


Fig. 4. Employed ICT specialists (Percentage of total employment) in 2024

4. Occupational Distribution of Demand for ICT Specialists in the Labour Market under Conditions of Digitalization of Work Processes

It has been observed that the informatization, automation, and robotization of production and/or services have, as an initial consequence, led to the complete or partial disappearance of certain occupations/professions and, consequently, of some jobs from the labour market. The immediate effect was a slight increase in unemployment, as advanced technologies, including those in the ICT domain, have contributed to the growth and diversification of production, and thus to rising incomes, which in turn enabled investments in new equipment and high-performance information systems. These developments inevitably fostered continuous growth, an increase in the number of new jobs, and investments in research, development, and innovation. Consequently, economic growth and efficiency were

achieved, along with higher wages for work tasks requiring higher education, as well as advanced competencies and skills. For all organizations, digital competencies have become mandatory, absolutely essential for fulfilling tasks in new jobs or occupations associated with emerging technologies.

If in 2021 approximately 9 million individuals were employed as ICT specialists in the EU, the European Union's objective is for this number to increase to around 20 million by 2030 [9]. Until then, concrete actions will be undertaken across EU countries to achieve the target whereby 80% of the EU population possesses at least basic digital skills, thereby facilitating adaptation to the new requirements of the labour market.

All these changes in the labour market have, however, required a series of local, central, and governmental policy measures designed to provide an appropriate organizational and legislative framework, capable of regulating and stimulating the actors involved (employers, employees, unemployed individuals, and the working-age population) to adapt dynamically to the new demands.

In the previous chapter, we examined the dynamics of four indicators directly related to the expansion of ICT and automation in the life of nations within EU countries over the period 2010 - 2024, and we produced a snapshot for the year 2024, when digitalization experienced significant development.

We now further analyse the quarterly data provided by Eurostat [7] regarding the occupational distribution (ISCO-08) of demand for ICT specialists in the labour market, as reflected in quarterly online job vacancy announcements for the period from the fourth quarter of 2019 to the second quarter of 2025 (Q4-2019, Q1-2020 … Q2-2025). It should be noted that, in Q4 2019, EU countries exhibited varying levels of informatization and automation, with developed and complex information systems, internet and computer networks of differing degrees of penetration, online commerce and payment systems, systems for organizing, storing, and protecting large volumes of data, cybersecurity systems, and Internet of Things (IoT) tools widely adopted across many sectors of activity, including renewable energy, transport, healthcare, and education.

The situation of these quarterly demands for ICT specialists on the online labor market, expressed as a percentage of total online labour demand, is as follows:

1. *Information and communications technology service managers.* This occupation exhibits slight fluctuations-either increases or decreases-which are certainly influenced by the greater or lesser availability of managers specialized in ICT technologies at the time these labour market demands are observed. Nevertheless, Czechia and Estonia stand out, showing a significantly higher demand for personnel in this category, accounting for approximately 40% of total online labour demand.
2. *Software and applications developers and analysts*. The demand in EU country markets for this category of ICT specialists-those responsible for the design,

programming, implementation, as well as the subsequent development and maintenance of complex information systems and applications that ensure the digital operation of production activities and/or services, along with the provision of technical assistance and support for their ongoing functioning and development-has been consistently high throughout the reported period, when expressed as a proportion of total online labour demand. This finding confirms the sustained interest in recruiting such ICT specialists, both within the business sector and at the governmental level, as there are also demands for specialists in local and central public administration, within key institutions underpinning the functioning of EU Member States. It is evident that, over the entire period analysed, this demand remained at an elevated level, reflecting the commitment of EU Member States to expanding and intensifying the process of digitalisation, both at the level of individual enterprises and organisations, and at national and European central levels. Notably, the Netherlands, Belgium, Austria, Poland, Finland, and Sweden stand out, exhibiting demand levels exceeding 60% of total online labour demand over the analysed period.

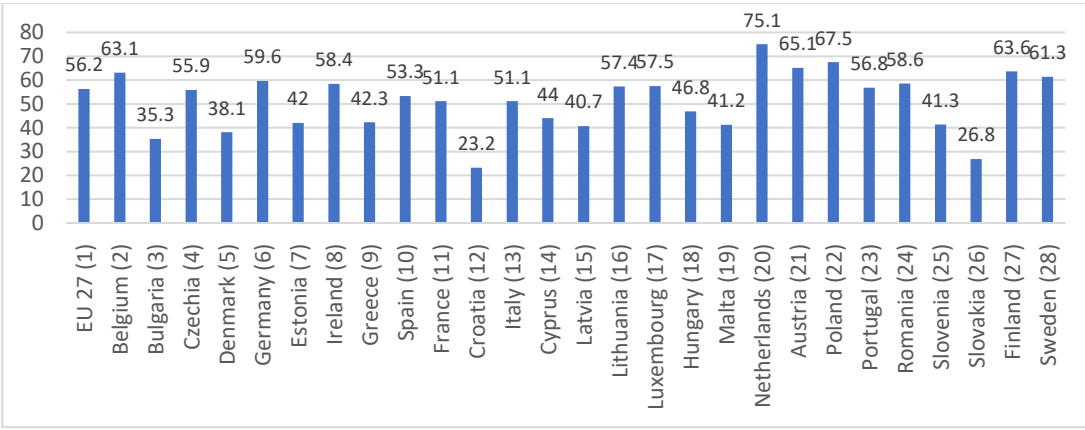


Fig. 5. The demand for ICT specialists: Software and Applications Developers and Analysts, in the second quarter of 2025.

3. *Database and network professionals*. As informatization expanded and increasingly complex and integrated information systems began to operate, specialists in data organisation, database management, and network functionality-ensuring the interconnectivity of all these networks and complex software products-became increasingly sought after on the labour market. In most EU countries, by 2020, the number of ICT specialists employed in this category was already substantial, their activity underpinning the ongoing expansion of digitalisation. For this reason, the demand for this type of ICT specialist over the analysed period (2020-2025) is comparatively lower as a proportion of total labour

demand, ranging between 7% and 12%. It is observed (Fig. 6) that in certain countries, demand for these specialists increased considerably in the second quarter of 2025 compared with the fourth quarter of 2019: Lithuania recorded an increase of 36%, Luxembourg 57%, Portugal 33%, Finland 31%, and Sweden 48%. This demand for specialists, similarly to the previously discussed category, confirms the continuous concern for recruiting professionals capable of advancing and intensifying the processes of informatization and automation across all work processes, as well as ensuring the connectivity of complex information systems, networks, and online working platforms across all sectors of activity.

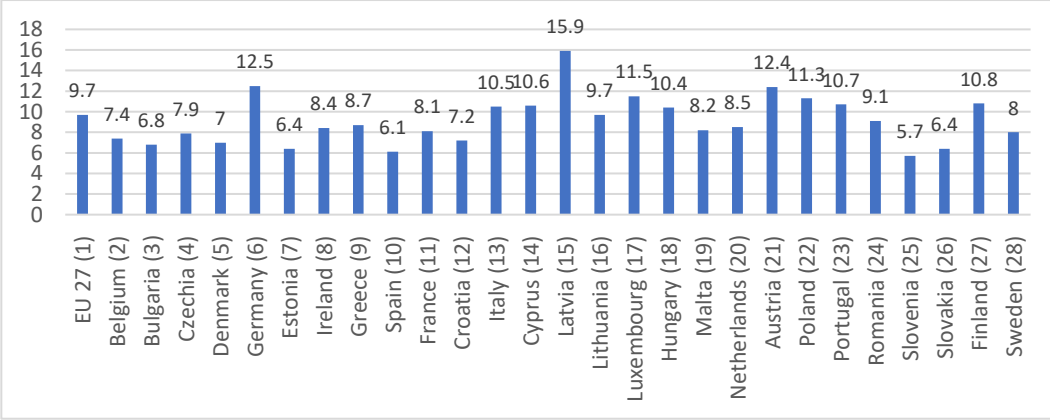


Fig.6. The demand for ICT specialists: Database and Network Professionals, in the second quarter of 2025.

4. *Information and communications technology operations and user support technicians.* This support staff-responsible for the maintenance and proper functioning of information systems and computer networks across all digitised, automated, or robotised activities-has consistently been a focus of employers throughout the analysed period, with relatively stable values from one quarter to another. However, online demand for these specialists, expressed as a percentage of total labour demand, increased in Ireland in the second quarter of 2025 compared with the fourth quarter of 2019 by 37%, in Slovakia by 62%, and in Croatia by a factor of 3.11. This demonstrates a sustained concern for the installation, implementation, and continuous maintenance of new hardware and software systems in operation, the number of which has grown steadily over time.
5. *Telecommunications and broadcasting technicians*. The demand for these specialists is relatively low, remaining between 1% and 3% of total online labour demand over the analysed period. Nevertheless, a notable increase can be observed beginning in the fourth quarter of 2021, with demand rising by 85% in France, by a factor of 4.2 in Finland, and by 5.7 times in Cyprus.

6. *Electronics and telecommunications installers and repairers.* The demand on the labour market for these specialists responsible for the maintenance of all electronic and telecommunications components has been relatively constant, albeit at a low level in terms of total labour demand, ranging between 0.1% and 1.8%. However, there are countries where investments in computer networks and their connectivity, in electronic equipment and necessary IoT devices, as well as in extensive online payment and e-commerce platforms, commenced later but increased significantly over the analysed period. This evolution consequently generated a very high demand for specialists in this category (Bulgaria - an increase of 7.7 times, Romania - 22 times, Belgium - 2.9 times, and Hungary - 2 times).
7. *Other information and communications technology specialists (OC2152, OC2153, OC2166, OC2356, OC2434, OC3114*)
   In EU countries, these specialists were demanded on the online labour market in varying proportions relative to total labour demand, ranging from 3% (Slovenia) to 45.2% (Bulgaria).

By correlating the number of ICT specialists employed during the period 2019-2024 with the online demand for such specialists, analysed by specific occupations, one may observe the concern of EU countries to meet the need for a specialised workforce possessing digital competencies. However, existing demand on the labour market for specialists with these competencies does not necessarily imply that such demand is fully satisfied. It should be noted that a high demand for specialists in a particular category, at a given moment in time in an EU country, does not necessarily indicate a significantly higher level of digitalisation compared with other countries; rather, it may be associated with the fact that that particular field of specialisation commenced later and progressed more slowly, thus generating a higher demand for specialised personnel at the time of analysis. Similarly, a lower proportion of demand for a certain type of specialist may be linked to the fact that the respective country initiated informatization earlier, trained specialists accordingly, and has most positions already filled with such professionals.

Enterprises, the business environment, and both local and central public administrations have undertaken significant efforts towards informatization through investments in information and communication technologies. They have supported the acquisition, installation, and maintenance of hardware and software components, created the jobs necessary for their efficient operation, and defined the competencies and skills required for their fulfilment. Digital infrastructure, advanced digital connectivity, the organisation of very large volumes of data, and the assurance of data protection and processing security-these extremely rapid developments have also led to the formulation of new and advanced digital competency requirements for these positions.

However, the advanced knowledge required in the fields of ICT, robotisation, and artificial intelligence is neither easily nor rapidly acquired. Consequently, there has been concern

regarding job losses in many sectors undergoing gradual informatization and automation, as well as concern among employers who encounter difficulties in finding specialised personnel with the required qualifications. Moreover, unemployed individuals and recent graduates face uncertainty in securing employment within a highly dynamic labour market, where competency and skills requirements are becoming increasingly stringent. Nevertheless, a range of specialised studies has demonstrated that digital evolution has generated a series of positive and beneficial effects on the workforce and on communities.

5. Labour market requirements concerning new competencies and skills in the context of the digitalisation of work processes

All transformations driven by the digitalisation process-across the business environment (production and/or services) in all fields of activity, within decision-making processes, and in both local and central public administration-have generated new essential requirements for the workforce, particularly those concerning advanced digital competencies. These are no longer optional; they have become mandatory and refer to advanced skills and abilities in the use of new digital technologies, including awareness of emerging occupational risks, which are continuously analysed by the European Agency for Safety and Health at Work (EU-OSHA). In this context, EU-OSHA monitors and highlights the impact that these developments may have on the nature and organisation of work, as well as the potential risks in the field of occupational health and safety [49][50].

Labour market transformations have now become structural, as they have produced changes in the occupational structure, with a major impact across all sectors of activity, through the emergence of new occupations and/or the modification of tasks associated with existing positions whose requirements have evolved. Thus, through automation, manual and/or repetitive work processes within transformed jobs are partially or fully replaced, while within newly created occupations, new requirements are formulated regarding the competencies and skills needed [51][52].

Goos analyses the impact of technological progress on the labour market through the concrete interaction between workers' competencies and the digital infrastructure in the workplace [53]. Where the workforce lacks adequate qualifications, Goos indicates that direct policy interventions are required in the fields of education and vocational training. In this regard, he highlights the increasing importance attributed at EU level to specialisation in scientific domains (mathematics, computer science, electronics), with the aim of creating a highly skilled labour supply. In the Polish economy, study [29] shows that the new era-defined by technologies based on data flows and their analysis-necessitates the professional training of employees in order to meet the new requirements for knowledge and skills. Thus, digitalisation directly influences not only the labour market, but also the education and

vocational training of both current workers and future job seekers [54][55]. Furthermore, as workers with lower levels of education are exposed to a higher risk of dismissal, it follows that advanced higher education, vocational training, and their continuous improvement constitute significant advantages in securing the future of work and career development [56].

As AI and IoT have become increasingly widespread across all sectors of activity, the importance of specialised competencies in ICT and AI has grown, and, concurrently, the importance of human competencies has increased even further [2]. Traditional occupations, in which manual and/or repetitive work processes can be replaced by AI, are disappearing [57][58][59], while a range of new professions is emerging, requiring new knowledge and skills. These developments generate new challenges in the occupational structure of the labour market, to which both employers and employees must adapt continuously and as rapidly as possible through the acquisition of new competencies. Jobs associated with these new professions generally offer higher-than-average salaries and present significantly faster and more sustained growth prospects than those in other sectors (e.g. specialists in cybersecurity, Big Data, large-scale data administration, designers of complex online platforms, cloud computing, etc.). It is estimated that, in the future, jobs will be digital or will increasingly rely on digital tools, while, at the same time, inequalities in terms of job quality and remuneration will increase [60][61][24]. Author D.H. refers to the rise in wages associated with higher education and the cognitive demands of workers' tasks [62], as well as with the competencies required of them.

In analysing the nature of competencies required by new occupations on the labour market, specialists classify them into technical competencies (hard skills) and non-technical abilities (soft skills), including interpersonal and social skills. Technical knowledge and abilities are acquired through specialised education within higher education institutions, as well as through training and/or professional development programmes, and qualification or requalification schemes [63][64].

As digitalisation intensifies, particularly in the context of the gradual introduction of AI, employers have somewhat reduced the relative importance of specialised ICT competencies, while significantly increasing the importance of human competencies [2]. These mainly refer to empathy, effective communication, teamwork, creativity and inventiveness, accountability, time and project management, conflict management, meeting deadlines, and adaptability to change [65][55][26][20].

Acemoglu and Autor analysed the gender distribution of workers in the ICT sector and observed [26] that women may possess a competitive advantage over men due to empathy and social skills, although they are less oriented towards university studies in Mathematics, Technology, Engineering, and Computer Science. The impact of new technologies is also

felt differently across age groups in the labour market: younger workers, both men and women, tend to adapt relatively easily to changes in technical and social competencies, whereas those aged over 60, particularly without relevant educational backgrounds, face greater difficulties in adapting to the new requirements of the labour market. All these analyses also take into account the higher levels of remuneration associated with new professions [24].

6. Legal and Regulatory Framework Governing Digitalisation and Labour Market Transformation in the European Union

6.1. Introduction to the Legal Dimension of Digital Labour Markets

The transformation of labour markets under the influence of digitalisation, automation, and artificial intelligence is not only an economic and technological process but also a fundamentally legal one. As highlighted in the previous sections, the expansion of ICT, the emergence of new occupations, and the transformation of skills requirements are accompanied by profound regulatory challenges affecting employment relationships, workplace organization, and social protection systems.

Within the European Union, the development of a coherent legal framework addressing these transformations has become a priority, as digitalisation reshapes traditional employment models and introduces new types of work arrangements, including platform work, remote work, hybrid employment, and AI-assisted decision-making processes. These developments raise critical legal questions concerning the classification of workers, protection of fundamental rights, data governance, occupational health and safety, and liability regimes in highly automated environments.

The EU has responded through a multi-layered regulatory approach combining binding legislation, soft law instruments, and strategic programmes such as the Digital Decade Policy Programme 2030 [72][66]. The purpose of this section is to analyse the main legal dimensions associated with the digital transformation of labour markets, in direct connection with the empirical findings previously presented.

6.2. Labour Law Adaptation in the Context of Digitalisation

6.2.1. Transformation of Employment Relationships

Digitalisation has significantly altered the traditional employer–employee relationship, historically based on physical presence, hierarchical supervision, and fixed working hours. The expansion of remote work, digital platforms, and algorithmic management systems has introduced increased flexibility, but also legal uncertainty.

One of the most debated issues concerns the classification of workers in the platform economy. Digital labour platforms frequently classify workers as independent contractors rather than employees, which has major legal consequences regarding:

- social security contributions
- minimum wage protection
- working time regulations
- access to collective bargaining
- protection against dismissal

These developments highlight the need for regulatory intervention at EU level in order to ensure fair working conditions and prevent the erosion of labour rights.

6.2.2. Remote Work and Teleworking Regulation

The expansion of telework has fundamentally transformed work organisation across EU Member States. This phenomenon intensified during the COVID-19 pandemic and continues to shape labour markets.

Telework raises legal concerns related to:

- working time regulation and monitoring
- employer supervision and digital control mechanisms
- occupational health and safety obligations
- cross-border legal jurisdiction issues

In response, regulatory initiatives at both EU and national levels increasingly recognize the right to disconnect, as well as employer obligations to ensure safe working conditions even outside traditional workplaces. These measures are closely linked to broader EU objectives regarding the improvement of working conditions in the digital economy [72].

6.3. Artificial Intelligence Regulation and Its Impact on Employment

The EU Artificial Intelligence Framework

Artificial intelligence has become a central component of digital transformation, with direct implications for labour markets. As previously highlighted in this study, AI influences both job creation and job destruction while reshaping skill requirements [2][4].

The emerging EU regulatory framework adopts a risk-based approach, distinguishing between different categories of AI systems depending on their impact on fundamental rights and social outcomes.

In the context of employment, several AI applications are considered particularly sensitive, including:

- recruitment and selection systems
- performance evaluation tools
- algorithmic management systems
- automated decision-making in HR processes

These applications require enhanced transparency, human oversight, and accountability, in order to prevent discrimination and ensure fairness in employment practices.

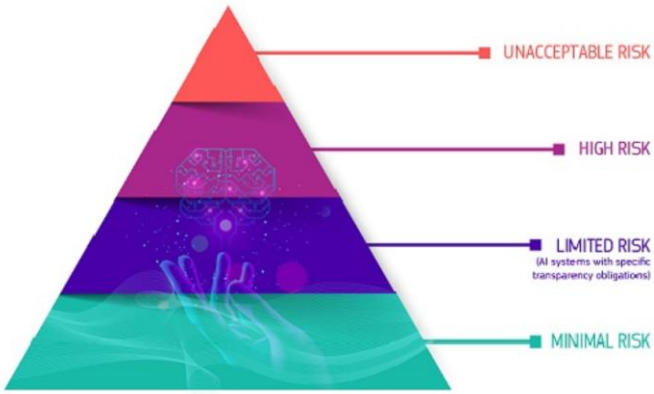


Fig. 7. EU AI regulatory risk pyramid
Source: European Commission – AI regulatory framework, https://digital-strategy.ec.europa.eu/en/policies/regulatory-framework-ai

Algorithmic Management and Worker Protection

The increasing reliance on algorithmic management systems introduces new risks related to:

- opacity of decision-making processes
- potential algorithmic bias
- asymmetry of information between employers and employees
- reduced human control over work allocation

These risks are particularly relevant in highly digitalised economies, where the use of ICT and AI technologies is most advanced [2][66].

In order to mitigate these risks, EU-level policies emphasize:

- transparency of automated decisions
- the right to human intervention
- the prevention of discriminatory outcomes
- the accountability of employers deploying AI systems

6.4. Data Protection and Privacy in the Digital Workplace

GDPR and Employee Data Processing

Digitalisation has led to the extensive processing of employee data, including performance data, communications, and behavioural patterns. As noted in EU-level policy instruments, safeguarding personal data has become a fundamental component of digital transformation [6][66].

The General Data Protection Regulation (GDPR) establishes key principles applicable to the employment context:

- lawfulness, fairness, and transparency
- purpose limitation
- data minimisation

- accuracy and storage limitation
- accountability

Employees benefit from rights such as access to their data and protection against fully automated decisions, which are essential in a digital labour market environment.

Fig. 8. Key GDPR principles applicable to employee data
Source: https://trainingcred.com/blog/employee-data-and-gdpr-compliance-ensuring-privacy-in-the-workplace

Workplace Monitoring and Surveillance

The use of digital monitoring tools-such as tracking software, productivity analytics, and biometric systems-has increased significantly.

However, EU legal frameworks require that such practices:

- respect proportionality and necessity
- serve legitimate business purposes
- ensure transparency towards employees
- preserve human dignity and privacy

These requirements reflect the broader EU commitment to balancing technological innovation with fundamental rights protection [49][50].

6.5. Occupational Health and Safety in Digital Work Environments

Digitalisation introduces new occupational risks that extend beyond traditional workplace hazards.

Psychosocial Risks

As highlighted by EU-OSHA, digitalisation contributes to:

- increased work intensity
- constant connectivity
- blurred boundaries between work and personal life
- higher risks of stress and burnout

These psychosocial risks are increasingly recognized as part of occupational health frameworks [49][50].

Ergonomic and Physical Risks

Remote work environments may lack proper ergonomic conditions, leading to:

- musculoskeletal disorders
- visual fatigue
- long-term health issues

Employers remain legally responsible for ensuring safe working conditions regardless of work location.

AI and Safety-Critical Systems

In sectors involving AI-assisted decision-making (e.g., transport, healthcare), safety requirements include:

- system certification and testing
- human oversight mechanisms
- clearly defined liability structures

These requirements reflect the integration of technological and legal standards in digitalised economies.

6.6. Skills, Education, and Legal Policy Frameworks

6.6.1. Lifelong Learning and Legal Policy

The transformation of labour markets requires continuous adaptation of workforce skills. EU initiatives emphasize lifelong learning as a legal and policy priority, supporting:

- reskilling and upskilling programmes
- access to digital education
- alignment of education systems with labour market needs [73][66]

These measures directly address the structural changes highlighted in previous sections.

6.6.2. Recognition and Standardisation of Digital Competencies

The need for harmonised skill frameworks has led to the development of European-level competency standards.

Feature	Traditional Employment	Digital Employment
Workplace	Physical	Remote / hybrid
Supervision	Direct (human)	Algorithmic / digital
Contracts	Standard labour contracts	Platform/flexible
Skills	Stable	Continuously evolving

Protection	Strong (standard)	Often fragmented

Table 2. Comparison between traditional and digital employment models
Source: authors research

These frameworks contribute to labour mobility and ensure consistency in competency recognition across EU Member States [69].

6.7. Social Protection and Inequality in the Digital Economy

Digitalisation may exacerbate inequalities if legal protections are not adapted.

Social Security and Non-Standard Employment

Non-traditional forms of employment may lack adequate social protection. EU-level policies aim to address:

- gaps in social security coverage
- portability of benefits
- inclusion of platform workers

Gender and Age Inequalities

As indicated in previous sections, digitalisation affects demographic groups differently [74]. Legal and policy frameworks seek to:

- reduce gender gaps in ICT employment
- support older workers' adaptation
- promote inclusive labour markets

Regardless of the demographic groups, the following skills are the most desired and relevant for the near future:

Fig. 9. Future skills demand
Source: World Economic Forum, https://www.weforum.org/stories/2023/05/growth-summit-2023-youth-work-skills/

6.8. Liability and Responsibility in Automated Systems

The increasing use of AI raises complex issues of legal responsibility.
Key challenges include:

- attribution of responsibility for AI decisions
- determination of liability in case of system failure
- evidentiary difficulties in automated environments

EU initiatives aim to clarify these issues through updated regulatory frameworks and liability rules, ensuring trust in digital technologies.

6.9. Synthesis: Legal Implications of Digital Labour Market Transformation

The transformation of labour markets under digitalisation is closely linked to the evolution of legal frameworks in the European Union.
The analysis highlights that:

- labour law is adapting to new forms of work
- AI regulation is central to employment governance
- data protection has become a core labour right
- occupational safety must address digital risks
- education policies are legally embedded in labour strategies
- social protection systems must evolve to prevent inequality

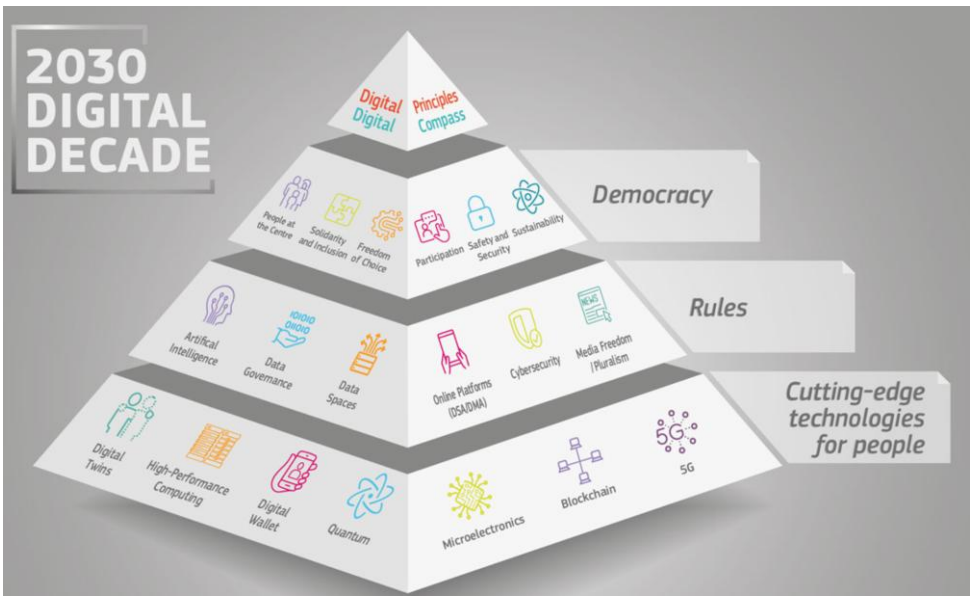


Fig. 10. EU Digital Decade targets (2030)
Source: https://www.seam.earth/sustainable-news/europes-digital-decade/

These legal developments provide the institutional foundation necessary to support the structural transformations of labour markets identified in the empirical analysis of this study.

7. Discussion

At present, an increasing number of employees are experiencing the disappearance of certain automated jobs, alongside changes in the requirements for digital knowledge and communication skills associated with their positions. At the same time, employers face vacant positions that require digital competencies, for which suitably qualified individuals-either with higher education in the relevant fields or capable of being trained through additional programmes-should be available.

Although approximately 55.6% of Europeans possess at least a basic level of digital skills [66], there remains a limited number of ICT specialists with advanced competencies, alongside a significant gender gap. This situation hampers progress in key ICT sectors, such as the storage, analysis, and protection of large volumes of data, robotisation, the expansion of IoT, cybersecurity, and artificial intelligence.

To support workers in the digital sector, as well as those applying for such positions, a number of specialists and researchers, together with educational and vocational training institutions, have identified, synthesised, and published these new competencies and skills, which are increasingly in demand on the labour market.

Bernard Marr argues that, at present, in-depth technical knowledge is less important for workers than understanding the impact that advanced ICT technologies will have on work in the future, and that most of the required skills will be non-technical, related to human states and/or activities that machines cannot perform [67]. However, many of these skills are not taught or developed within traditional educational systems, which are primarily focused on training specialists in the field.

The UK Government's Department for Education has developed a guide aimed at explaining and exemplifying these fundamental digital competencies required in a continuously evolving labour market [68], as well as additional skills such as communication, information management, problem-solving using online services, awareness of data visibility in online environments, and the risks to data protection and confidentiality. As ICT evolves more rapidly and advances towards artificial intelligence, both specialised technological competencies and workers' personal skills become increasingly important.

In this context, it is necessary to establish a unified definition at EU level of ICT occupations and professional profiles, as well as the specific and personal competencies required of workers. Study [69] analyses three existing reference frameworks for defining similar competencies within the EU: *the e-Competence Framework e-CF (EN 16234-1:2016), ESCO (European Skills, Competences and Occupations classification)*, and the *European ICT Body of Knowledge* - and highlights the need to create a unified standard that integrates all these competencies, skills, knowledge, and qualifications. This framework, referred to as e-Skills Match, could ensure the use of a common language for a consistent understanding of the specific requirements of different ICT roles across EU countries, facilitate the mobility of professionals within the EU, and support the alignment of education with the specific demands of work in terms of the new competencies and skills required [70].

Technological development, automation, and the digitalisation of all economic, social, and cultural domains, together with investments in innovation and research and development across EU countries, will lead to the disappearance of certain occupations and a large number of jobs, while also generating new challenges and opportunities in an ever-changing labour market. These developments will give rise to the jobs of the future, most of which will be digital in nature or will rely heavily on digital tools.

For workers with a low level of education, the risk of job loss is significantly higher than for those with higher levels of education, which necessitates the acquisition and development of new competencies demanded by the labour market through continuous education, higher education, or vocational training. In order to ensure the continuous and up-to-date qualification of the workforce, a system of lifelong learning is required, in which ICT educational programmes are designed with a modular, flexible structure that can be easily adapted to the acquisition of new competencies required by the labour market [71].

8. Conclusions

The evolution of occupations will undoubtedly entail the adoption of measures, policies, and regulations within EU countries aimed at coordinating and stimulating the adaptation of workers, the unemployed, and the working-age population to the new technical and non-technical competency requirements demanded by the labour market.

Accordingly, the European Parliament, the European Commission, and the EU Member States have established and are cooperating in the implementation of a set of policies necessary to achieve the EU's digital objectives by 2030 [72][9]. There are new ICT domains in which hundreds of thousands of jobs remain vacant and are difficult to fill on the labour market, requiring specialists in areas such as cybersecurity, data analysis, machine learning and artificial intelligence, Big Data, business intelligence analysis, software and applications development, data analytics, as well as engineering in green energy and electric vehicles [18][65][73].

Consequently, the education system in EU countries must become more flexible and adapt to the new requirements of the labour market, in order to provide-alongside the specialised knowledge necessary for automation and digitalisation-the non-technical competencies and skills required by emerging professions.

All these developments will contribute to reducing the adjustment period of the labour market to the new context of technological and ICT-driven development, thereby supporting the transition towards balancing labour supply and demand.

Researchers have also examined the relationship between the growth of competencies and wage increases in new occupations requiring higher levels of education, vocational training, or qualifications. Furthermore, they have found that new labour market positions are increasingly attracting young and working-age women into employment across various highly automated and digitalised sectors [74].

All these aspects demonstrate that the labour market, in its continuous transformation, has profound implications not only for employment and unemployment, economic growth, and specialisation in ICT-related fields, but also for population well-being, the promotion of gender equality in the labour market, and the reduction of gender disparities.

The conclusions of this analysis may assist policymakers in EU countries in shaping policies aimed at stimulation, adaptation, and increased flexibility in higher education and vocational training systems, as well as in investment in research and development and occupational health and safety activities. This implies that the analysis should be continued in order to identify and measure the factors contributing to the growth of digitalisation, the transformation of specialised higher education, the sectors driving economic and ICT development, and labour market behaviour with regard to reducing gender disparities.

Abbreviations

AI = Artificial Intelligence
IoT = Internet of Things
EU-OSHA = European Agency for Safety and Health
ILO = International Labour Organization
WEF = World Economic Forum

References

[1] OECD (2019). Preparing for the Changing Nature of Work in the Digital Era, https://www.oecd.org/going-digital/changing-nature-of-work-in-the-digital-era.pdf

[2] OECD (2023), OECD Employment Outlook 2023: Artificial Intelligence and the Labour Market, OECD Publishing, Paris, https://doi.org/10.1787/08785bba-en

[3] ILO, 2019a, Global Commission on the Future of Work, Working for a brighter future, International Labour Office. Geneva 2019.

[4] ILO, 2023, Generative AI and Jobs: A global analysis of potential effects on job quantity and quality, 2023, https://www.ilo.org/global/publications/working-papers/WCMS_890761/lang--en/index.htm

[5] European Union, 2009, The impact of ICT on employment, Final report, 2009, https://op.europa.eu/en/publication-detail/-/publication/2e16f508-1acc-4042-afd1-19ce3c78e841

[6] Eurostat, 2025, Digitalisation in Europe - 2025 edition, https://ec.europa.eu/eurostat/web/interactive-publications/digitalisation-2025#businesses-online

[7] Eurostat, 2026, ICT specialists in employment, April 2025, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=ICT_specialists_in_employment

[8] European Commission, 2018. *Coordinated plan on artificial intelligence*. [online] https://digital-strategy.ec.europa.eu/ro/library

[9] European Commission, 2022, Digital Economy and Society Index 2022, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_4560

[10] Parlamentul European, 2020, https://www.europarl.europa.eu/topics/ro/article/20200918STO87404/inteligenta-artificiala-oportunitati-si-pericole

[11] WEF, 2016, World Economics Forum, The future of jobs: employment, skills and workforce strategy for the Fourth Industrial Revolution, Cologny/Geneva Switzerland January 2016

[12] WEF, 2023a, World Economic Forum, Assessing the level of innovativeness and digitalization of enterprises in the European Union States, https://www.weforum.org/

[13] A. Adams, 2018, Technology and the labour market, Oxford Review of Economic Policy, Vol. 34, No. 3, Technology and the Labour Market , 2018, pp. 349-361, Published By: Oxford University Press, https://www.jstor.org/stable/48592194

[14] S. Torrejón Pérez; I. González Vázquez, 2021, The Impact of Technology on the Present and the Future of Work and Skills, Chapter 7: in New Directions in the Future of Work, DOI: https://doi.org/10.1108/978-1-80071-298-020211015, 2021, ISBN: 978-1-80071-298-0

[15] Preeti Yadav and Archana Aher, 2025, Impact of Technology on Labour Market, International Journal of Advanced Research in Science, Communication and Technology (IJARSCT), Vol 5, Issue 1, March 2025

[16] CECCAR Business Magazine, 2024, AI va avea impact asupra a 40% din locurile de muncă la nivel mondial, mai ales în economiile avansate, CECCAR Business Magazine

NR 2, 17-23 IAN. 2024, CONECTAREA LA ERA DIGITALĂ, https://www.ceccarbusinessmagazine.ro/ai-va-avea-impact-asupra-a-40-din-locurile-de-munca-la-nivel-mondial-mai-ales-in-economiile-avansate/a/FkZvGX8NaP3Y4msVKb6q

[17] Yu, M. (2023). Positive and Negative Effects of Digitalization on Human Resource Management. Contributions to Management Science, 15-26. https://doi.org/10.1007/978-3-031-23432-3_2

[18] Smartemp, 2025, Macrotrendurile care transforma piata muncii, https://smartemp.ro/2025/04/03/impact-inteligenta-artificiala-joburi/

[19] Frey C., Osborne M, (2017), 'The Future of Employment: How Susceptible Are Jobs to Computerisation?', Technological Forecasting & Social Change, 114, 254-80.

[20] Autor D. H., F Levy, R.J. Murnane, 2003, The Skill Content of Recent Technological Change: An Empirical Exploration, *The Quarterly Journal of Economics*, Volume 118, Issue 4, November 2003, Pages 1279-1333, https://doi.org/10.1162/003355303322552801

[21] Ciucă V, Iordan M, Lincaru C, Chilian MN, (2025). Viitorul muncii în contextul schimbărilor demografice și al avansului tehnologic : perspective din România, Bucureşti : Institutul European din România. https://ier.gov.ro/wp-content/uploads/2025/03/SPOS_3_Viitorul-muncii_2025-1.pdf

[22] Badea, L., Șerban-Oprescu, G.L., Iacob, S.E., Mishra, S., Stanef, M.R., 2024. Artificial Intelligence and the Future of Work - A Sustainable Development Perspective. *Amfiteatru Economic*, 26(Special Issue No. 18), pp. 1031-1047, DOI: https://doi.org/10.24818/EA/2024/S18/1031 , oct 2024

[23] M Eden, P Gaggl, 2018, On the welfare implications of automation, Review of Economic Dynamics, Volume 29, 2018, Pages 15-43, ISSN 1094-2025, https://doi.org/10.1016/j.red.2017.12.003

[24] Taniguchi H., Yamada K., 2022, ICT capital-skill complementarity and wage inequality: Evidence from OECD countries, Labour Economics, Vol 76, 2022, 102151, ISSN 0927-5371, https://doi.org/10.1016/j.labeco.2022.102151

[25] Postuła M, Chmielewski W, Puczyński P & Cieślik R,.(2021), The Impact of Information and Communication Technologies (ICT) on Energy Poverty and Unemployment in Selected European Union Countries, *Energies*, *14*(19), 6110, https://doi.org/10.3390/en14196110

[26] Acemoglu, D., Autor, D.H., 2011. Skills, Tasks and Technologies: Implications for Employment and Earnings. In: Card, D., Ashenfelter, O. (Eds.), Handbook of Labor Economics. Elsevier, pp. 1043-1171

[27] A.R. Hesda, 2023, Impact of ICT on Unemployment: A Global Empirical Analysis, Jurnal Ketenagakerjaan, Vol 18, No. 2, 2023 Online ISSN: 2722-8770, https://journals.kemnaker.go.id/index.php/naker/article/view/216/108

[28] B Wang, Y Liu and S K. Parker, 2020, How Does the Use of Information Communication Technology Affect Individuals? A Work Design Perspective, Academy of Management Annals, Vol. 14, No. 2, Aug 2020 , https://doi.org/10.5465/annals.2018.0127

[29] Hetmańczyk P, 2024, Digitalization and its impact on labour market and education. Selected aspects. *Educ Inf Technol* 29, 11119-11134 (2024), https://doi.org/10.1007/s10639-023-12203-8

[30] Sadia R., Tuli F.A. & Lal K. (2023). Digitization History and its Impact on the Economy, Employment, and Society, Global Disclosure of Economics and Business, 12(1), 15-24, https://doi.org/10.18034/gdeb.v12i1.707

[31] R. Bachmann, M. Gonschor, P. Lewandowski, K. Madoń, 2024, The impact of Robots on Labour market transitions in Europe, Structural Change and Economic Dynamics, Vol 70, 2024, Pages 422-441, ISSN 0954-349X, https://doi.org/10.1016/j.strueco.2024.05.005 .

[32] Arntz, M., T. Gregory and U. Zierahn (2016), "The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis", OECD Social, Employment and Migration Working Papers, No. 189, May 2016, OECD Publishing, Paris, https://doi.org/10.1787/5jlz9h56dvq7-en.

[33] Popescu (Iacobescu), I.M., Zavatin (Chilea), I., Manea, D.I., Pamfilie, R. and Jurconi, A., 2024. Adapting the Competences of the Employed Personnel in the Context of the Integration of Artificial Intelligence in Organisations. *Amfiteatru Economic*, 26(67), pp. 817-831, DOI: https://doi.org/10.24818/EA/2024/67/817

[34] Beleva, I. (2022). Digitalization and its impact on employment (quantitative and qualitative aspects). Economic Thought Journal, 67(3), 269-300. https://doi.org/10.56497/etj2267302

[35] Deming, D. J. (2017), 'The Growing Importance of Social Skills in the Labor Market', Quarterly Journal of Economics, 132(4), 1593-640

[36] Istudor, N., Socol, A.G., Marinaș, M.C. and Socol, C., 2024. Analysis of the Adequacy of Employees' Skills for the Adoption of Artificial Intelligence in Central and Eastern European Countries. *Amfiteatru Economic*, 26(67), pp. 703-720, DOI: https://doi.org/10.24818/EA/2024/67/703

[37] R. Bahrini, A.A. Qaffas, 2019, Impact of Information and Communication Technology on economic growth: Evidence from developing countries, Economies, 7(1), 21 (2019) 1-19, https://doi.org/10.3390/economies7010021

[38] A. Colecchia, P. Schreyer, 2002, ICT Investment and Economic Growth in the 1990s: Is the United States a Unique Case?: A Comparative Study of Nine OECD Countries, Review of Economic Dynamics, Vol 5, Issue 2, 2002, Pages 408-442, https://doi.org/10.1006/redy.2002.0170 .

[39] Evangelista, R., Guerrieri, P., & Meliciani, V. (2014). The economic impact of digital technologies in Europe, Economics of Innovation and New Technology, 23(8), 802-824, https://doi.org/10.1080/10438599.2014.918438

[40] Botezatu, M. A., Ivanescu, I. M., Ivanescu, M. M., & Diaconescu, F. (2021), Challenges of Digital Economies: An Analysis of the Factors that Influence Economic Development of the EU Member States, in Under the Pressure of Digitalization: Challenges and Solutions at Organizational and Industrial Levels, First Edition, Pag: 32-39, 5th Edition International e-conference "Enterprises in the Global Economy *under Pandemic*" EGE, (December 14th, 2020), https://www.webofscience.com/wos/woscc/full-record/WOS:000683887600005

[41] J Bessen, 2019, Automation and jobs: when technology boosts employment, *Economic Policy*, Vol 34, Issue 100, October 2019, Pages 589-626, https://doi.org/10.1093/epolic/eiaa001

[42] Ș,C Gherghina, M.A Botezatu, L.N Simionescu, 2021, Exploring the Impact of Electronic Commerce on Employment Rate: Panel Data Evidence from European Union Countries, Journal of Theoretical and Applied Electronic Commerce Research, 2021, 16(7), pg. 3157-3183, https://doi.org/10.3390/jtaer16070172

[43] Biagi, F.; Falk M, 2017, The impact of ICT and e-commerce on employment in Europe. J. Policy Model 2017, 39, 1-18.

[44] Stanila, L.; Andreica, M.E.; Cristescu, A., 2014, Econometric analysis of the employment rate for the E.U. countries, Procedia - Social and Behavioral Sciences, 2014, Vol 109, 178-182, ISSN 1877-0428, https://doi.org/10.1016/j.sbspro.2013.12.440

[45] Y Feng, D Lagakos, JE Rauch, 2024, Unemployment and Development, *The Economic Journal*, Volume 134, Issue 658, February 2024, Page 614-647, https://doi.org/10.1093/ej/uead076

[46] Moffitt R., Ko W, 2024, Unemployment benefits and unemployment. IZA World of Labor 2024: 13 doi: 10.15185/izawol.13.v2, https://wol.iza.org/articles/unemployment-benefits-and-unemployment/long

[47] Sârbu, R., Ciobanu, G., Popescu, M.L. and Troacă, V.A., 2020. The Impact of Digitization on the Labor Market Paths and Development Opportunities, In: R. Pamfilie, V. Dinu, L. Tăchiciu, D. Pleșea, C. Vasiliu eds. 6th BASIQ International Conference on New Trends in Sustainable Business and Consumption. Messina, Italy, 4-6 June 2020. Bucharest: ASE, pp. 214-221

[48] Chernousova, K.S., Shilman, R.M. (2024). Impact of Digitalization on the Labor Market Development and Improvement. In: Mantulenko, V.V., Horák, J., Kučera, J. (eds) Proceedings of the XI International Scientific Conference "Digital Transformation of the Economy: Challenges, Trends and New Opportunities" (ISCDTE 2024). ISCDTE 2024. Lecture Notes in Networks and Systems, vol 1063, 215-220, Springer, Cham. https://doi.org/10.1007/978-3-031-65662-0_29

[49] EU-OSHA, 2026a, Digitalisation of work, https://osha.europa.eu/en/themes/digitalisation-work

[50] EU-OSHA, 2026b, ICT & Digitalisation, https://osha.europa.eu/ro/emerging-risks/developments-ict-and-digitalisation-work

[51] McKinsey Global Institute (2017), A Future that Work: Automation, Employment and Productivity, McKinsey & Company.

[52] Dengler K, Matthes B, 2018, The impacts of digital transformation on the labour market: Substitution potentials of occupations in Germany, Technological Forecasting and Social Change, Volume 137, 2018, Pag 304-316, https://doi.org/10.1016/j.techfore.2018.09.024

[53] M. Goos, 2018, The impact of technological progress on labour markets: policy challenges, *Oxford Review of Economic Policy*, Vol 34, Issue 3, 2018, Pag 362-375, https://doi.org/10.1093/oxrep/gry002

[54] Ermolaeva, A.S. (2023). Additional Education in Digital Technologies as Competitiveness in the Labor Market. In: Maximova, S.G., Raikin, R.I., Chibilev, A.A., Silantyeva, M.M. (eds) Advances in Natural, Human-Made, and Coupled Human-Natural Systems Research. Lecture Notes in Networks and Systems, vol 234. Springer, Cham. https://doi.org/10.1007/978-3-030-75483-9_67

[55] Nedelkoska, L. and G. Quintini (2018), "Automation, skills use and training", OECD Social, Employment and Migration Working Papers, No. 202, OECD Publishing, Paris, https://doi.org/10.1787/2e2f4eea-en

[56] OECD (2016), "Automation and Independent Work in a Digital Economy", Policy Brief on The Future of Work, OECD Publishing, Paris, 2016.

[57] Marsden O, 2025, The Vanishing Professions: A Catalogue of Jobs That No Longer Make Sense, December 16, 2025, https://www.selavy.fr/post/the-vanishing-professions-a-catalogue-of-jobs-that-no-longer-make-sense

[58] Jerbashian V, 2019. Automation and job polarization: on the decline of middling occupations in Europe. Oxf. Bull. Econ. Stat. 81 (5), 1095-1116. https://doi.org/10.1111/obes.12298

[59] WEF, 2023b, These are the jobs most likely to be lost - and created - because of AI, May 4, 2023, https://www.weforum.org/stories/2023/05/jobs-lost-created-ai-gpt/

[60] World Bank Group, 2015,The Effects of Technology on Employment and Implications for Public Employment Services, Report prepared for the G20 Employment Working Group Meeting Istanbul, Turkey 6-8 May 2015

[61] ILO, 2019b, Paul Schulte & John Howard, THE IMPACT OF TECHNOLOGY ON , WORK AND THE WORKFORCE, International Labour Organization, 9 March 2019, https://www.ilo.org/resource/statement/impact-technology-work-and-workforce

[62] Autor D. H., (2014), Skills, Education, and the Rise of Earnings Inequality Among the Other 99 Percent, Science, 344(6186), 843-51, DOI: 10.1126/science.1251868, https://www.science.org/doi/10.1126/science.1251868

[63] S. Surakka, 2007, What subjects and skills are important for software developers?, Communications of the ACM, Vol 50(1), Pag 73-78, https://doi.org/10.1145/1188913.1188920

[64] A.Llorens-Garcia, X. Llinas-Audet and F. Sabate, 2009, "Professional and Interpersonal Skills for ICT Specialists," in *IT Professional*, vol. 11, no. 6, pp. 23-30, Nov.-Dec. 2009, doi: 10.1109/MITP.2009.132, https://ieeexplore.ieee.org/document/5339325

[65] O. Barbăneagră, 2023, Structural Transformations of the Labor Market in the Age of Artificial Intelligence, Economic Security in the Context of Systemic Transformations, International Conference, December 07-08, 2023, Chișinău, Moldova, DOI: https://doi.org/10.53486/escst2023.02 , Academy of Economic Studies of Moldova, Moldova

[66] European Commission, 2025, Digital Decade - Policy programme, https://digital-strategy.ec.europa.eu/en/policies/digital-decade-policy-programme

[67] Marr, B., 2022. *Future skills: The 20 skills and competencies everyone needs to succeed in a Digital World*. Hoboken, NJ: Wiley, 2022, ISBN: 9781119870418

[68] GOV.UK, Department for Education, 2019, Guidance. Essential digital skills framework, 2019, https://www.gov.uk/government/publications/essential-digital-skills-framework/essential-digital-skills-framework

[69] L.Fernández, J. Gómez-Pérez, A. Castillo-Martínez, 2017, e-Skills Match: A framework for mapping and integrating the main skills, knowledge and competence standards and models for ICT occupations, Computer Standards & Interfaces, Vol 51, 2017, Pages 30-42, ISSN 0920-5489, https://doi.org/10.1016/j.csi.2016.11.004

[70] KG. Tijdens; Judith De Ruijter; Esther De Ruijter, 2012, Measuring work activities and skill requirements of occupations, European Journal of Training and Development (2012) 36 (7): 751-763, https://doi.org/10.1108/03090591211255575

[71] Petersen A. Willi, Peter Revill, Tony Ward, Carsten Wehmeye, 2005, ICT and e-business skills and training in Europe, Cedefop, European Centre for the Development of Vocational Training, 2005, https://www.cedefop.europa.eu/sl/publications/5149

[72] European Commission, 2023, Digital Decade Policy Programme 2030, https://digital-strategy.ec.europa.eu/en/library/digital-decade-policy-programme-2030

[73] European Commission, 2016, A NEW SKILLS AGENDA FOR EUROPE: Working together to strengthen human capital, employability and competitiveness, https://ec.europa.eu/social/BlobServlet?docId=15692&langId=en

[74] Albinowski M, Lewandowski P, 2024, The impact of ICT and robots on labour market outcomes of demographic groups in Europe, Labour Economics, Vol 87, 2024, 102481, https://doi.org/10.1016/j.labeco.2023.102481

[75] Eurostat (2026), Database on Economic and Finance, https://ec.europa.eu/eurostat/data/database

Bibliography

A. Adams, 2018, Technology and the labour market, Oxford Review of Economic Policy, Vol. 34, No. 3, Technology and the Labour Market , 2018, pp. 349-361, Published By: Oxford University Press, https://www.jstor.org/stable/48592194

A. Colecchia, P. Schreyer, 2002, ICT Investment and Economic Growth in the 1990s: Is the United States a Unique Case?: A Comparative Study of Nine OECD Countries, Review of Economic Dynamics, Vol 5, Issue 2, 2002, Pages 408-442, https://doi.org/10.1006/redy.2002.0170 .

A.Llorens-Garcia, X. Llinas-Audet and F. Sabate, 2009, "Professional and Interpersonal Skills for ICT Specialists," in IT Professional, vol. 11, no. 6, pp. 23-30, Nov.-Dec. 2009, doi: 10.1109/MITP.2009.132, https://ieeexplore.ieee.org/document/5339325

A.R. Hesda, 2023, Impact of ICT on Unemployment: A Global Empirical Analysis, Jurnal Ketenagakerjaan, Vol 18, No. 2, 2023 Online ISSN: 2722-8770, https://journals.kemnaker.go.id/index.php/naker/article/view/216/108

Acemoglu, D., Autor, D.H., 2011. Skills, Tasks and Technologies: Implications for Employment and Earnings. In: Card, D., Ashenfelter, O. (Eds.), Handbook of Labor Economics. Elsevier, pp. 1043-1171

Albinowski M, Lewandowski P, 2024, The impact of ICT and robots on labour market outcomes of demographic groups in Europe, Labour Economics, Vol 87, 2024, 102481, https://doi.org/10.1016/j.labeco.2023.102481

Arntz, M., T. Gregory and U. Zierahn (2016), "The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis", OECD Social, Employment and Migration Working Papers, No. 189, May 2016, OECD Publishing, Paris, https://doi.org/10.1787/5jlz9h56dvq7-en.

Autor D. H., (2014), Skills, Education, and the Rise of Earnings Inequality Among the Other 99 Percent, Science, 344(6186), 843-51, DOI: 10.1126/science.1251868, https://www.science.org/doi/10.1126/science.1251868

Autor D. H., F Levy, R.J. Murnane, 2003, The Skill Content of Recent Technological Change: An Empirical Exploration, The Quarterly Journal of Economics, Volume 118, Issue 4, November 2003, Pages 1279-1333, https://doi.org/10.1162/003355303322552801

B Wang, Y Liu and S K. Parker, 2020, How Does the Use of Information Communication Technology Affect Individuals? A Work Design Perspective, Academy of Management Annals, Vol. 14, No. 2, Aug 2020 , https://doi.org/10.5465/annals.2018.0127

Badea, L., Șerban-Oprescu, G.L., Iacob, S.E., Mishra, S., Stanef, M.R., 2024. Artificial Intelligence and the Future of Work - A Sustainable Development Perspective. Amfiteatru Economic, 26(Special Issue No. 18), pp. 1031-1047, DOI: https://doi.org/10.24818/EA/2024/S18/1031 , oct 2024

Beleva, I. (2022). Digitalization and its impact on employment (quantitative and qualitative aspects). Economic Thought Journal, 67(3), 269-300. https://doi.org/10.56497/etj2267302

Bessen, J. (2023), AI and Jobs: The Role of Demand (NBER Working Paper)

Biagi, F.; Falk M, 2017, The impact of ICT and e-commerce on employment in Europe. J. Policy Model 2017, 39, 1-18.

Botezatu, M. A., Ivanescu, I. M., Ivanescu, M. M., & Diaconescu, F. (2021), Challenges of Digital Economies: An Analysis of the Factors that Influence Economic Development of the EU Member States, in Under the Pressure of Digitalization: Challenges and Solutions at Organizational and Industrial Levels, First Edition, Pag: 32-39, 5th Edition International e-conference "Enterprises in the Global Economy under Pandemic" EGE, (December 14th, 2020), https://www.webofscience.com/wos/woscc/full-record/WOS:000683887600005

CECCAR Business Magazine, 2024, AI va avea impact asupra a 40% din locurile de muncă la nivel mondial, mai ales în economiile avansate, CECCAR Business Magazine Nr 2, 17-23 ian. 2024, Conectarea la era digitală, https://www.ceccarbusinessmagazine.ro/ai-va-avea-impact-asupra-a-40-din-locurile-de-munca-la-nivel-mondial-mai-ales-in-economiile-avansate/a/FkZvGX8NaP3Y4msVKb6q

Cedefop (2022), Digital Skills: Challenges and Opportunities in Europe

Chernousova, K.S., Shilman, R.M. (2024). Impact of Digitalization on the Labor Market Development and Improvement. In: Mantulenko, V.V., Horák, J., Kučera, J. (eds) Proceedings of the XI International Scientific Conference "Digital Transformation of the Economy: Challenges, Trends and New Opportunities" (ISCDTE 2024). ISCDTE 2024. Lecture Notes in Networks and Systems, vol 1063, 215-220, Springer, Cham. https://doi.org/10.1007/978-3-031-65662-0_29

Ciucă V, Iordan M, Lincaru C, Chilian MN, (2025). Viitorul muncii în contextul schimbărilor demografice și al avansului tehnologic : perspective din România, Bucureşti : Institutul European din România. https://ier.gov.ro/wp-content/uploads/2025/03/SPOS_3_Viitorul-muncii_2025-1.pdf

Deming, D. J. (2017), 'The Growing Importance of Social Skills in the Labor Market', Quarterly Journal of Economics, 132(4), 1593-640

Dengler K, Matthes B, 2018, The impacts of digital transformation on the labour market: Substitution potentials of occupations in Germany, Technological Forecasting and Social Change, Volume 137, 2018, Pag 304-316, https://doi.org/10.1016/j.techfore.2018.09.024

Ermolaeva, A.S. (2023). Additional Education in Digital Technologies as Competitiveness in the Labor Market. In: Maximova, S.G., Raikin, R.I., Chibilev, A.A., Silantyeva, M.M. (eds) Advances in Natural, Human-Made, and Coupled Human-Natural Systems Research. Lecture Notes in Networks and Systems, vol 234. Springer, Cham. https://doi.org/10.1007/978-3-030-75483-9_67

EU-OSHA, 2026a, Digitalisation of work, https://osha.europa.eu/en/themes/digitalisation-work

EU-OSHA, 2026b, ICT & Digitalisation, https://osha.europa.eu/ro/emerging-risks/developments-ict-and-digitalisation-work

European Commission, 2016, A NEW SKILLS AGENDA FOR EUROPE: Working together to strengthen human capital, employability and competitiveness, https://ec.europa.eu/social/BlobServlet?docId=15692&langId=en

European Commission, 2018. Coordinated plan on artificial intelligence. https://digital-strategy.ec.europa.eu/ro/library

European Commission, 2022, Digital Economy and Society Index 2022, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_4560

European Commission, 2023, AI Watch: Artificial Intelligence and the Future of Work in the EU

European Commission, 2023, Digital Decade Policy Programme 2030, https://digital-strategy.ec.europa.eu/en/library/digital-decade-policy-programme-2030

European Commission, 2025, Digital Decade - Policy programme, https://digital-strategy.ec.europa.eu/en/policies/digital-decade-policy-programme

European Union, 2009, The impact of ICT on employment, Final report, 2009, https://op.europa.eu/en/publication-detail/-/publication/2e16f508-1acc-4042-afd1-19ce3c78e841

Eurostat, 2025, Digitalisation in Europe - 2025 edition, https://ec.europa.eu/eurostat/web/interactive-publications/digitalisation-2025#businesses-online

Eurostat, 2026, ICT specialists in employment, April 2025, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=ICT_specialists_in_employment

Evangelista, R., Guerrieri, P., & Meliciani, V. (2014). The economic impact of digital technologies in Europe, Economics of Innovation and New Technology, 23(8), 802-824, https://doi.org/10.1080/10438599.2014.918438

Frey C., Osborne M, (2017), 'The Future of Employment: How Susceptible Are Jobs to Computerisation?', Technological Forecasting & Social Change, 114, 254-80.

GOV.UK, Department for Education, 2019, Guidance. Essential digital skills framework, 2019, https://www.gov.uk/government/publications/essential-digital-skills-framework/essential-digital-skills-framework

Hetmańczyk P, 2024, Digitalization and its impact on labour market and education. Selected aspects. Educ Inf Technol 29, 11119-11134 (2024), https://doi.org/10.1007/s10639-023-12203-8

ILO, 2019a, Global Commission on the Future of Work, Working for a brighter future, International Labour Office. Geneva 2019

ILO, 2019b, Paul Schulte & John Howard, THE IMPACT OF TECHNOLOGY ON , WORK AND THE WORKFORCE, International Labour Organization, 9 March 2019, https://www.ilo.org/resource/statement/impact-technology-work-and-workforce

ILO, 2023, Generative AI and Jobs: A global analysis of potential effects on job quantity and quality, 2023, https://www.ilo.org/global/publications/working-papers/WCMS_890761/lang--en/index.htm

ILO, 2024, World Employment and Social Outlook: Trends 2024

IMF, 2024, Artificial Intelligence and the Future of Work (Staff Discussion Note)

Istudor, N., Socol, A.G., Marinaș, M.C. and Socol, C., 2024. Analysis of the Adequacy of Employees' Skills for the Adoption of Artificial Intelligence in Central and Eastern European Countries. Amfiteatru Economic, 26(67), pp. 703-720, DOI: https://doi.org/10.24818/EA/2024/67/703

J Bessen, 2019, Automation and jobs: when technology boosts employment, Economic Policy, Vol 34, Issue 100, October 2019, Pages 589-626, https://doi.org/10.1093/epolic/eiaa001

Jerbashian V, 2019. Automation and job polarization: on the decline of middling occupations in Europe. Oxf. Bull. Econ. Stat. 81 (5), 1095-1116. https://doi.org/10.1111/obes.12298

KG. Tijdens; Judith De Ruijter; Esther De Ruijter, 2012, Measuring work activities and skill requirements of occupations, European Journal of Training and Development (2012) 36 (7): 751-763, https://doi.org/10.1108/03090591211255575

L.Fernández, J. Gómez-Pérez, A. Castillo-Martínez, 2017, e-Skills Match: A framework for mapping and integrating the main skills, knowledge and competence standards and models for ICT occupations, Computer Standards & Interfaces, Vol 51, 2017, Pages 30-42, ISSN 0920-5489, https://doi.org/10.1016/j.csi.2016.11.004

M Eden, P Gaggl, 2018, On the welfare implications of automation, Review of Economic Dynamics, Volume 29, 2018, Pages 15-43, ISSN 1094-2025, https://doi.org/10.1016/j.red.2017.12.003

M. Goos, 2018, The impact of technological progress on labour markets: policy challenges, Oxford Review of Economic Policy, Vol 34, Issue 3, 2018, Pag 362-375, https://doi.org/10.1093/oxrep/gry002

Marr, B., 2022. Future skills: The 20 skills and competencies everyone needs to succeed in a Digital World. Hoboken, NJ: Wiley, 2022, ISBN: 9781119870418

Marsden O, 2025, The Vanishing Professions: A Catalogue of Jobs That No Longer Make Sense, December 16, 2025, https://www.selavy.fr/post/the-vanishing-professions-a-catalogue-of-jobs-that-no-longer-make-sense

McKinsey Global Institute, 2017, A Future that Work: Automation, Employment and Productivity, McKinsey & Company.

McKinsey Global Institute, 2023. Generative AI and the Future of Work in America

Moffitt R., Ko W, 2024, Unemployment benefits and unemployment. IZA World of Labor 2024: 13 doi: 10.15185/izawol.13.v2, https://wol.iza.org/articles/unemployment-benefits-and-unemployment/long

Nedelkoska, L. and G. Quintini (2018), "Automation, skills use and training", OECD Social, Employment and Migration Working Papers, No. 202, OECD Publishing, Paris, https://doi.org/10.1787/2e2f4eea-en

O. Barbăneagră, 2023, Structural Transformations of the Labor Market in the Age of Artificial Intelligence, Economic Security in the Context of Systemic Transformations, International Conference, December 07-08, 2023, Chișinău, Moldova, DOI: https://doi.org/10.53486/escst2023.02 , Academy of Economic Studies of Moldova, Moldova

OECD, 2016, "Automation and Independent Work in a Digital Economy", Policy Brief on The Future of Work, OECD Publishing, Paris, 2016.

OECD, 2019. Preparing for the Changing Nature of Work in the Digital Era, https://www.oecd.org/going-digital/changing-nature-of-work-in-the-digital-era.pdf

OECD, 2023, OECD Employment Outlook 2023: Artificial Intelligence and the Labour Market, OECD Publishing, Paris, https://doi.org/10.1787/08785bba-en

OECD, 2024, Employment Outlook 2024: The Net-Zero Transition and the Labour Market

Parlamentul European, 2020, https://www.europarl.europa.eu/topics/ro/article/20200918STO87404/inteligenta-artificiala-oportunitati-si-pericole

Petersen A. Willi, Peter Revill, Tony Ward, Carsten Wehmeye, 2005, ICT and e-business skills and training in Europe, Cedefop, European Centre for the Development of Vocational Training, 2005, https://www.cedefop.europa.eu/sl/publications/5149

Popescu (Iacobescu), I.M., Zavatin (Chilea), I., Manea, D.I., Pamfilie, R. and Jurconi, A., 2024. Adapting the Competences of the Employed Personnel in the Context of the Integration of Artificial Intelligence in Organisations. Amfiteatru Economic, 26(67), pp. 817-831, DOI: https://doi.org/10.24818/EA/2024/67/817

Postuła M, Chmielewski W, Puczyński P & Cieślik R,.(2021), The Impact of Information and Communication Technologies (ICT) on Energy Poverty and Unemployment in Selected European Union Countries, Energies, 14(19), 6110, https://doi.org/10.3390/en14196110

Preeti Yadav and Archana Aher, 2025, Impact of Technology on Labour Market, International Journal of Advanced Research in Science, Communication and Technology (IJARSCT), Vol 5, Issue 1, March 2025

R. Bachmann, M. Gonschor, P. Lewandowski, K. Madoń, 2024, The impact of Robots on Labour market transitions in Europe, Structural Change and Economic Dynamics, Vol 70, 2024, Pages 422-441, ISSN 0954-349X, https://doi.org/10.1016/j.strueco.2024.05.005 .

R. Bahrini, A.A. Qaffas, 2019, Impact of Information and Communication Technology on economic growth: Evidence from developing countries, Economies, 7(1), 21 (2019) 1-19, https://doi.org/10.3390/economies7010021

Ș,C Gherghina, M.A Botezatu, L.N Simionescu, 2021, Exploring the Impact of Electronic Commerce on Employment Rate: Panel Data Evidence from European Union Countries, Journal of Theoretical and Applied Electronic Commerce Research, 2021, 16(7), pg. 3157-3183, https://doi.org/10.3390/jtaer16070172

S. Surakka, 2007, What subjects and skills are important for software developers?, Communications of the ACM, Vol 50(1), Pag 73-78, https://doi.org/10.1145/1188913.1188920

S. Torrejón Pérez; I. González Vázquez, 2021, The Impact of Technology on the Present and the Future of Work and Skills, Chapter 7: in New Directions in the Future of Work, Doi: https://doi.org/10.1108/978-1-80071-298-020211015, 2021, ISBN: 978-1-80071-298-0

Sadia R., Tuli F.A. & Lal K. (2023). Digitization History and its Impact on the Economy, Employment, and Society, Global Disclosure of Economics and Business, 12(1), 15-24, https://doi.org/10.18034/gdeb.v12i1.707

Sârbu, R., Ciobanu, G., Popescu, M.L. and Troacă, V.A., 2020. The Impact of Digitization on the Labor Market Paths and Development Opportunities, In: R. Pamfilie, V. Dinu, L. Tăchiciu, D. Pleșea, C. Vasiliu eds. 6th BASIQ International Conference on New Trends in Sustainable Business and Consumption. Messina, Italy, 4-6 June 2020. Bucharest: ASE, pp. 214-221

Smartemp, 2025, Macrotrendurile care transforma piata muncii, https://smartemp.ro/2025/04/03/impact-inteligenta-artificiala-joburi/

Stanila, L.; Andreica, M.E.; Cristescu, A., 2014, Econometric analysis of the employment rate for the E.U. countries, Procedia - Social and Behavioral Sciences, 2014, Vol 109, 178-182, ISSN 1877-0428, https://doi.org/10.1016/j.sbspro.2013.12.440

Taniguchi H., Yamada K., 2022, ICT capital-skill complementarity and wage inequality: Evidence from OECD countries, Labour Economics, Vol 76, 2022, 102151, ISSN 0927-5371, https://doi.org/10.1016/j.labeco.2022.102151

WEF, 2016, World Economics Forum, The future of jobs: employment, skills and workforce strategy for the Fourth Industrial Revolution, Cologny/Geneva Switzerland January 2016

WEF, 2023a, World Economic Forum, Assessing the level of innovativeness and digitalization of enterprises in the European Union States, https://www.weforum.org/

WEF, 2023b, These are the jobs most likely to be lost - and created - because of AI, May 4, 2023, https://www.weforum.org/stories/2023/05/jobs-lost-created-ai-gpt/

World Bank Group, 2015,The Effects of Technology on Employment and Implications for Public Employment Services, Report prepared for the G20 Employment Working Group Meeting Istanbul, Turkey 6-8 May 2015

World Economic Forum (2024), Future of Jobs Report 2024

Y Feng, D Lagakos, JE Rauch, 2024, Unemployment and Development, The Economic Journal, Volume 134, Issue 658, February 2024, Page 614-647, https://doi.org/10.1093/ej/uead076

Yu, M. (2023). Positive and Negative Effects of Digitalization on Human Resource Management. Contributions to Management Science, 15-26. https://doi.org/10.1007/978-3-031-23432-3_2

EUROPEAN DIGITAL LEGISLATION 2026: A LANDMARK YEAR FOR THE EUROPEAN DIGITAL GOVERNANCE FRAMEWORK

Alexandru TĂBUȘCĂ[1]
Silvia TĂBUȘCĂ[2]

Abstract

The European Union has developed one of the most ambitious and comprehensive digital governance architectures globally. Between 2022 and 2025, numerous legislative instruments were adopted with the objective of creating a competitive, secure, human-centric, and trustworthy digital ecosystem. The year 2026 represents a significant milestone because several of these regulations enter advanced implementation and enforcement phases. This paper examines the evolution of the European digital regulatory framework and analyzes the practical implications of the Data Act, the Artificial Intelligence Act, the Digital Services Act, the Digital Markets Act, the revised eIDAS Regulation and the European Digital Identity Wallet, the Data Governance Act, NIS2, the Cyber Resilience Act, and the emerging Digital Fairness agenda. The study highlights the transformation of digital regulation from isolated legislative initiatives into a coherent governance system intended to support innovation while safeguarding fundamental rights, cybersecurity, transparency, competition, and digital sovereignty. Furthermore, the article evaluates the expected impact on public institutions, private enterprises, technology providers, digital platforms, and European citizens. The research concludes that 2026 marks the transition from digital strategy formulation to large-scale operational implementation of the European Digital Decade objectives.

Keywords: Digital Governance, AI Act, Data Act, Digital Services Act, European Digital Identity, Digital Regulation

JEL Classification: K24, K38, O33, O38, L86

1. Introduction

Digital transformation has become one of the defining characteristics of modern society. Governments, businesses, educational institutions and citizens increasingly depend on interconnected digital infrastructures, cloud services, artificial intelligence solutions and data-driven decision-making processes. While technological innovation provides substantial economic and social opportunities, it also generates risks associated with

[1] PhD Associate Professor, Romanian-American University, Romania, alex.tabusca@rau.ro; corresponding author
[2] PhD, Lecturer, Center for Human Rights and Migration, cdom@rau.ro

privacy, cybersecurity, misinformation, market concentration and algorithmic decision-making.

The European Union has responded to these challenges by developing an extensive regulatory framework capable of balancing innovation with accountability, data protection, cybersecurity, competition and fundamental rights protections [1] [3] [5]. Unlike approaches based primarily on self-regulation or market-driven governance, the European model emphasizes legal certainty, consumer protection, transparency and the protection of fundamental rights.

The importance of 2026 derives from the fact that many major legislative initiatives are no longer merely policy proposals or recently adopted instruments but enter substantive implementation phases with binding compliance obligations for organizations across the European Union [1] [3] [7] [9]. Several regulations now reach decisive implementation stages, transforming legal requirements into concrete operational obligations. Organizations throughout Europe must therefore move beyond regulatory awareness and adopt practical compliance mechanisms.

This paper examines the most important legislative initiatives shaping the European digital environment during 2026 and evaluates their expected impact on the future of digital governance in Europe.

2. The Evolution of the European Digital Regulatory Model

The European Commission's Digital Decade initiative established a comprehensive vision for Europe's digital transformation by 2030, focusing on digital infrastructure, digital skills, business digitalization and digital public services [9]. Key priorities include digital skills, secure infrastructure, business digitalization, and digital public services. The 2026 State of the Digital Decade Report highlights continuing investments and national implementation programs designed to achieve these objectives.

The Digital Decade framework does not operate independently. Instead, it connects numerous regulatory instruments that collectively form a coherent governance architecture. These instruments seek to address different dimensions of the digital ecosystem including artificial intelligence governance, data sharing, cybersecurity, online platform accountability and trusted electronic identification services [1] [3] [5] [7] [11]:

- Data governance
- Artificial intelligence
- Platform accountability
- Cybersecurity

- Digital identity
- Competition policy
- Consumer protection

Regulation	Main Objective	Primary Stakeholders	2026 Relevance
AI Act	Trustworthy AI	AI developers and deployers	Major enforcement phase
Data Act	Data sharing and portability	Manufacturers, cloud providers	Operational implementation
DSA	Platform accountability	Online platforms	Ongoing compliance
DMA	Fair digital competition	Gatekeepers	Continued enforcement
eIDAS 2.0	Digital identity	Citizens, governments	Wallet deployment
NIS2	Cybersecurity governance	Essential entities	Full implementation
CRA	Secure digital products	Manufacturers	Compliance preparation

Tabel 1. Comparative Analysis of Major EU Digital Regulations

Source: European Commission regulatory framework documents.

Domain	Example Requirement	Expected Difficulty
AI Governance	Risk assessments	High
Data Sharing	Interoperability	High
Cybersecurity	Incident reporting	Medium
Digital Identity	Wallet integration	Medium
Platform Governance	Transparency obligations	High
Cloud Services	Switching mechanisms	Medium

Tabel 2. Organizational Compliance Challenges Associated with EU Digital Legislation

Source: Author's analysis based on EU legislative requirements.

The emergence of this integrated approach reflects the European belief that technological development requires institutional trust, legal certainty and transparent governance structures.

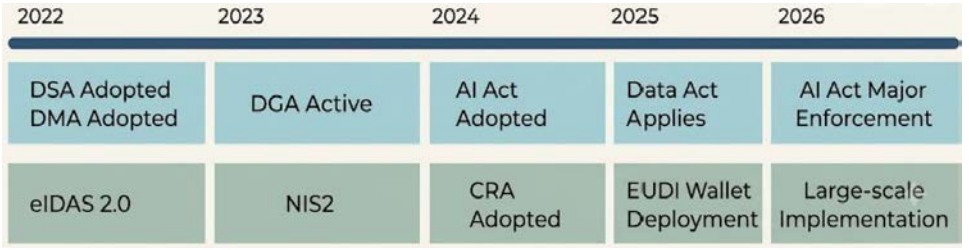


Figure 1. Timeline of Major EU Digital Legislative Milestones (2022-2026)

Source: Author's analysis based on European Commission Digital Strategy, AI Act implementation materials, Data Act documentation and Digital Decade reports

We should also mention that the frameworks regarding the digital infrastructure at EU level are not only directly relevant for legal entities, governments and policy makers. Different stakeholders are also impacted by the different regulations, at different levels of course.

Stakeholder	Main Benefits	Main Challenges
Citizens	Identity portability, safer online services	Learning new digital tools
SMEs	Better market access	Compliance costs
Large Platforms	Regulatory certainty	Extensive oversight
Public Authorities	Improved digital services	Implementation complexity
Researchers	Better data access	Governance requirements
Cloud Providers	Expanded market opportunities	Portability obligations

Figure 2. Benefits and Challenges Created by the 2026 Digital Framework

Source: Author's synthesis from EU digital legislation package.

3. The EU Data Act and the Future of the European Data Economy

The Data Act represents one of the most significant legislative initiatives aimed at creating a functional European data economy by facilitating fair access to data generated through

connected devices and digital services [1] [2]. The regulation entered into force in January 2024 and became applicable in September 2025. Its practical implications continue to expand throughout 2026.

The Data Act seeks to address a central challenge of the digital economy: access to data generated by connected devices and digital services. Traditionally, manufacturers and service providers exercised substantial control over data generated by users. The Data Act attempts to rebalance these relationships.

3.1 Objectives of the Data Act

According to the European Commission, the Data Act establishes a harmonized framework for data access, interoperability and cloud service portability throughout the European Single Market [1] [2]:

- Increasing user access to generated data.
- Facilitating business-to-business data sharing.
- Improving cloud service portability.
- Reducing vendor lock-in.
- Supporting innovation.
- Strengthening the Single Market for Data.

These objectives are expected to stimulate innovation in sectors such as manufacturing, logistics, healthcare, energy and agriculture.

3.2 Economic Implications

The economic significance of data has transformed information into a strategic resource comparable to traditional factors of production. The Data Act is expected to increase innovation opportunities by reducing barriers to access industrial and machine-generated data [1] [2] [12]. By facilitating access to industrial and IoT-generated data, the Data Act may reduce barriers to innovation and support the emergence of new business models based on advanced analytics and AI.

Provision	Expected Impact
User access to device data	Increased transparency
Cloud portability	Reduced lock-in
Fair contractual terms	Improved competition
Public-sector access mechanisms	Enhanced crisis response
Interoperability requirements	Market integration

Table 3. Main Data Act Provision

Source: Adapted from European Commission Data Act documentation

4. AI Act Implementation Milestones in 2026

Artificial intelligence has rapidly become a strategic technology capable of transforming virtually all economic sectors and therefore represents a major focus of European digital governance policy [3] [4]. Consequently, the European Union adopted the AI Act, the first comprehensive regulatory framework dedicated specifically to artificial intelligence.

The AI Act follows a risk-based approach that categorizes AI systems according to their potential impact on society, distinguishing between unacceptable-risk, high-risk, limited-risk and minimal-risk systems [3] [4]. Certain applications are prohibited, while high-risk systems are subject to extensive compliance obligations. Major implementation and enforcement phases become applicable during 2026.

The AI Act represents more than a compliance instrument. It is also a strategic effort to establish Europe as a global leader in trustworthy and human-centric artificial intelligence governance [3] [4] [12]. It is also a strategic effort to establish Europe as a global leader in trustworthy AI governance.

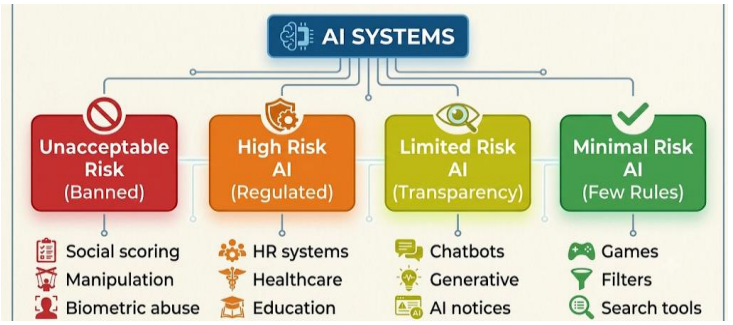


Figure 3. Risk-Based Classification Structure Established by the AI Act

Source: Adapted from Regulation (EU) 2024/1689 on Artificial Intelligence and related implementation guidance

4.1 Categories of AI Systems

The framework identifies:

- Prohibited AI practices
- High-risk AI systems
- Limited-risk applications
- Minimal-risk applications

This tiered structure enables regulators to focus oversight resources where risks are greatest.

Risk Category	Typical Examples	Regulatory Obligations
Unacceptable Risk	Social scoring, manipulative systems	Prohibited
High Risk	Recruitment, healthcare, education, critical infrastructure	Full compliance requirements
Limited Risk	Chatbots, AI-generated content	Transparency obligations
Minimal Risk	Spam filters, recommendation engines	Voluntary best practices

Table 3. Overview of AI Act Categories and Compliance Expectations

Source: Adapted from Regulation (EU) 2024/1689 and implementation guidance

4.2 High-Risk Systems

From 2026 onward, providers and deployers of high-risk AI systems face extensive governance obligations including documentation, risk management and human oversight requirements [3], [4].

- Risk management frameworks
- Technical documentation
- Human oversight mechanisms
- Data quality controls
- Monitoring procedures

These requirements are expected to significantly influence sectors such as healthcare, education, recruitment, finance and critical infrastructure.

Sector	Typical AI Uses	Expected Regulatory Impact
Healthcare	Medical diagnosis	Very High
Education	Student assessment	High
Banking	Credit scoring	High
Public Administration	Automated decision support	High
Manufacturing	Predictive maintenance	Medium
Retail	Recommendation systems	Medium
Media	Content generation	Medium

Table 4. Sector-Specific Impact Assessment of AI Regulation

Source: Author's analysis based on AI Act risk categories and implementation guidance

For the present time, and most likely throughout the foreseeable future if we adopt a rational and realistic perspective, artificial intelligence systems should continue to operate under the ultimate oversight and authority of a human decision-maker. While AI can provide valuable support, analysis, and automation, the final responsibility for critical decisions should remain with human controllers, particularly in highly sensitive and high-stakes sectors such as military operations, healthcare services, and the banking industry, where errors, ethical considerations, and accountability can have significant consequences for individuals and society as a whole.

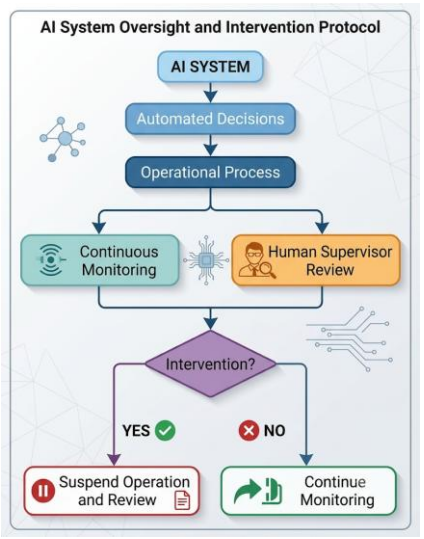


Figure 4. Human-on-the-Loop Supervision Model

Source: Author's synthesis based on post-deployment monitoring and supervisory requirements for high-risk AI applications

In order to establish a consistent and standardized framework for the human monitoring, supervision, and control of artificial intelligence systems, it is essential to develop clear governance guidelines that define responsibilities, decision-making processes, and accountability mechanisms. Such guidelines should ensure that AI systems, regardless of their level of autonomy or complexity, remain subject to effective human oversight throughout their entire lifecycle, from design and deployment to operation and evaluation.

A key element of this governance framework is the application of the four-eyes principle, which requires that critical decisions, approvals, or interventions involving AI systems be reviewed and validated by at least two qualified individuals. This approach helps reduce the risk of human error, bias, negligence, or misuse, while increasing transparency and trust in the decisions supported or generated by artificial intelligence. The *four-eyes principle* is particularly important in high-risk contexts, where the consequences of an incorrect AI-driven recommendation or action may have significant legal, financial, operational, or societal implications.

At the same time, effective AI governance should be structured according to a *governance pyramid*, which distributes responsibilities across multiple organizational levels. At the operational level, specialists and system operators are responsible for the day-to-day monitoring and management of AI applications. At the managerial level, supervisors and department leaders ensure compliance with organizational policies, ethical requirements, and regulatory obligations. At the strategic level, senior executives and governing bodies define the overall vision, risk appetite, and accountability framework for the use of artificial intelligence within the organization.

The combination of the four-eyes principle and the governance pyramid creates a robust control environment in which oversight is not concentrated in a single individual or organizational layer. Instead, responsibilities are distributed, checks and balances are embedded into decision-making processes, and multiple stakeholders contribute to ensuring that AI systems operate safely, ethically, transparently, and in accordance with both organizational objectives and legal requirements. By integrating these two concepts into formal guidelines, organizations can strengthen human control over AI technologies while promoting trust, accountability, and responsible innovation.

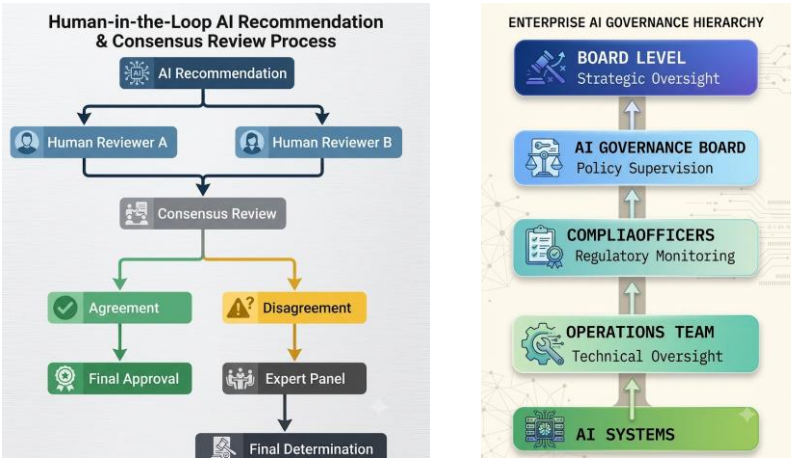


Figure 5. Four-Eyes Principle & Human governance Pyramid for Critical AI Decisions

Source: Author's interpretation of governance mechanisms for AI accountability

5. Digital Services Act and Platform Accountability

The Digital Services Act (DSA) establishes a modern governance framework for online intermediaries, marketplaces, social networks, search engines, hosting services and very large online platforms operating within the European Union [5] [6]. The regulation seeks to create a safer digital environment while preserving innovation and freedom of expression. Organizations covered by the DSA must comply with transparency, reporting and risk-management obligations designed to protect users and reduce systemic online risks [5] [6]:

- Illegal content reporting mechanisms.
- Transparency requirements.
- Risk assessments.
- Independent audits for very large online platforms.
- Enhanced user rights.

The DSA is particularly relevant in combating misinformation, illegal products, online fraud and other systemic risks. DSA addresses a wide range of challenges associated with the digital environment, including the spread of misinformation, the sale and promotion of illegal products, online fraud, and other systemic risks that may negatively affect individuals, businesses, and society as a whole. By establishing a comprehensive set of obligations for online platforms, the DSA seeks to create a safer, more transparent, and

more accountable digital ecosystem in which users are better protected against harmful and unlawful content.

With regard to *misinformation*, the DSA encourages greater transparency in content moderation practices and risk management measures, particularly for very large online platforms whose services can significantly influence public opinion and social discourse. These requirements are intended to reduce the dissemination of false or misleading information that may undermine democratic processes, public health initiatives, or social stability. The DSA is also highly relevant in combating the availability of *illegal products and services* offered through online marketplaces. By imposing stronger due-diligence obligations on digital platforms, the regulation aims to improve the detection, reporting, and removal of unlawful goods, thereby enhancing consumer protection and increasing trust in online commerce.

Furthermore, the regulation plays an important role in addressing *online fraud and deceptive practices*, including scams, identity theft schemes, fraudulent advertising, and other forms of digital misconduct. Through enhanced transparency requirements and accountability mechanisms, the DSA helps limit the opportunities for malicious actors to exploit online services and deceive users.

Beyond these specific issues, the DSA targets a broader category of *systemic risks*, such as threats to fundamental rights, public security, civic discourse, and the integrity of online information ecosystems. By requiring platforms to assess, mitigate, and report such risks on a continuous basis, the regulation promotes a more responsible approach to digital governance and contributes to the long-term resilience, safety, and trustworthiness of the online environment.

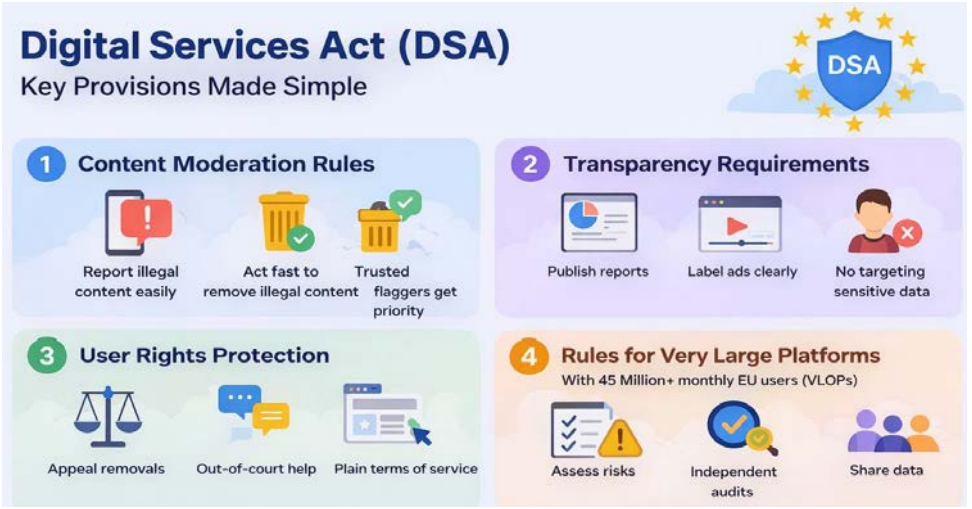


Figure 1. Core Governance Objectives of the Digital Services Act

Source: https://wplegalpages.com/blog/what-is-digital-services-act/

6. Digital Markets Act and Competition in Digital Ecosystems

Complementing the DSA, the Digital Markets Act (DMA) seeks to address structural competition concerns involving major digital platforms designated as gatekeepers, thereby improving market contestability and reducing anti-competitive practices within digital ecosystems [5] [6].

The DMA introduces obligations intended to:

- Prevent unfair self-preferencing.
- Ensure interoperability.
- Facilitate business-user access.
- Support market contestability.

The combined operation of the DSA and the DMA illustrates the EU's comprehensive approach toward digital platform governance.

7. European Digital Identity Wallet and eIDAS 2.0

One of the most ambitious European digital initiatives concerns digital identity. Under eIDAS 2.0, Member States are expected to deploy European Digital Identity Wallets capable of supporting secure authentication and electronic credential management across borders [7] [8]. Deployment activities intensify throughout 2026.

The wallet is expected to support:

- Digital identification.
- Digital driving licences.
- Educational credentials.
- Professional certifications.
- Electronic signatures.

The European Commission expects the EUDI Wallet ecosystem to enhance trust, interoperability and service accessibility throughout the Digital Single Market [7] [8] [9]:

- Cross-border mobility.

- Digital public services.
- Financial onboarding.
- Trust in online transactions.

The initiative also supports broader Digital Decade objectives concerning secure digital public services.

The EUDI Wallet represents a key pillar of the European Union's digital transformation strategy, enabling citizens to securely store and share digital credentials such as identity documents, diplomas, driving licences, and professional certificates. Romania has actively supported the implementation of this initiative through participation in European pilot projects and the development of a national EUDI Wallet ecosystem aligned with the eIDAS 2.0 framework. Several organizations are already contributing to this effort, including Mastercard Europe, which signed a partnership with the Romanian Government to support the deployment of the national digital wallet infrastructure, as well as certSIGN, Banca Transilvania, Visa, and other technology and financial-sector partners involved in testing interoperability, digital identity verification, and secure electronic transactions based on the EUDI Wallet concept.

8. Data Governance Act and European Data Spaces

The Data Governance Act complements the Data Act by strengthening trust-based data sharing mechanisms and supporting the development of Common European Data Spaces [1] [2] [12]. The regulation promotes:

- Data intermediaries.
- Data altruism initiatives.
- Public sector data re-use.
- Cross-border data collaboration.

The long-term objective is the establishment of Common European Data Spaces across strategic sectors, including healthcare, mobility, energy and public administration.

These data spaces may significantly improve innovation capacity while maintaining European values regarding privacy and security.

9. NIS2 and the Cyber Resilience Agenda

Cybersecurity increasingly represents a strategic concern for governments and organizations due to the growing dependence on interconnected digital infrastructures and digital services [10] [11] [14]. The NIS2 Directive expands cybersecurity obligations across critical sectors and introduces stronger governance expectations regarding risk management and incident reporting. While the NIS2 Directive expands cybersecurity obligations across critical sectors the Cyber Resilience Act (CRA) introduces lifecycle security requirements for digital products and software solutions [10] [11], throughout their lifecycle.

Instrument	Primary Focus
NIS2	Organizational cybersecurity
Cyber Resilience Act	Product security
eIDAS 2.0	Trust services
Data Act	Secure data sharing
AI Act	AI-related risk management

Table 2. Cybersecurity Regulatory Landscape

Source: author's own research

The combined effect is the emergence of a comprehensive cybersecurity ecosystem. Within this ecosystem, the NIS2 Directive plays a central role by strengthening cybersecurity requirements across a broad range of essential and important entities. NIS2 establishes a harmonized framework for risk management, incident reporting, supply-chain security, business continuity, and corporate accountability, thereby increasing the overall resilience of critical sectors such as energy, transport, healthcare, banking, and digital infrastructure. By requiring organizations to adopt proactive cybersecurity measures and by enhancing cooperation among national authorities and EU Member States, NIS2 contributes significantly to the creation of a more secure and coordinated European cyber environment.

Complementing this regulatory framework, the CRA extends cybersecurity obligations to manufacturers and providers of digital products containing hardware and software components. The CRA introduces a security-by-design and security-by-default approach, requiring products to meet essential cybersecurity requirements throughout their lifecycle, including vulnerability management and security updates. As a result, cybersecurity becomes an intrinsic feature of digital products rather than an afterthought. Together, NIS2 and the CRA create a layered approach to cyber resilience, addressing both organizational

cybersecurity governance and product security, while fostering trust, reducing systemic vulnerabilities, and strengthening the digital resilience of the European economy.

Looking ahead, the Cyber Resilience Act is expected to drive the development of a European digital market in which cybersecurity assurance becomes a fundamental competitive requirement, encouraging continuous innovation in secure-by-design technologies, automated vulnerability management, and trustworthy digital products capable of adapting to emerging cyber threats throughout their entire lifecycle.

10. Digital Fairness and Future Regulatory Developments

European institutions have increasingly focused on digital fairness, particularly regarding online platforms, dark patterns, manipulative interfaces and consumer vulnerabilities [9] [10].

The proposed Digital Fairness Act may represent the next major regulatory initiative affecting platform governance, consumer rights and digital market behavior after the implementation of the current legislative package [9] [10]. Discussions continue within broader digital simplification and Digital Omnibus initiatives.

Potential focus areas include:

- Algorithmic transparency.
- Consumer manipulation.
- Personalized advertising.
- Influencer marketing.
- Digital consumer rights.

These developments demonstrate that European digital governance remains dynamic rather than static.

11. Implications for Public Administration and Businesses

Public administrations face increasing responsibilities regarding digital service delivery, digital identity deployment, cybersecurity governance, data management and responsible AI adoption [3] [7] [9] [10].

Businesses similarly encounter growing compliance requirements associated with AI governance, data sharing obligations, platform accountability, cybersecurity resilience and

digital identity integration [1] [3] [5] [7] [11]. However, these obligations are accompanied by opportunities to enhance transparency, improve digital trust and access new markets.

Organizations that proactively adapt their governance models are likely to gain competitive advantages within the evolving digital economy.

The implementation of the NIS2 Directive and the CRA also has significant implications for both public administrations and businesses, requiring a shift from reactive cybersecurity practices to proactive risk management and resilience strategies. Public authorities must strengthen their governance frameworks, improve incident response capabilities, and ensure effective cybersecurity oversight across critical public services.

For businesses, particularly those operating in critical and digital sectors, compliance with NIS2 and CRA entails greater responsibility for cybersecurity risk assessment, supply-chain security, vulnerability management, and reporting obligations. Organizations will need to invest in secure-by-design technologies, employee awareness, and continuous monitoring systems to meet the new regulatory requirements.

At the same time, these regulatory frameworks create opportunities by increasing trust in digital services, enhancing operational resilience, and fostering a more secure digital marketplace. Over the long term, NIS2 and CRA are expected to contribute to a stronger cybersecurity culture across both the public and private sectors, supporting sustainable digital transformation and greater confidence in Europe's digital economy.

12. Conclusions

The year 2026 represents a landmark moment in the development of European digital governance. The Data Act, AI Act, Digital Services Act, Digital Markets Act, eIDAS 2.0 framework, Data Governance Act, NIS2 and related initiatives collectively establish one of the world's most sophisticated regulatory environments.

Rather than addressing isolated technological challenges or sector-specific regulatory concerns, these instruments collectively establish a comprehensive and interconnected governance architecture designed to guide and shape the development of the future digital society. Their combined impact extends beyond individual policy objectives, creating a coherent framework that promotes legal certainty, digital trust, and sustainable technological progress across the European Union.

Their implementation reflects a distinct European approach to digital governance, one that seeks to balance and reconcile multiple strategic priorities, including innovation, market competitiveness, cybersecurity, transparency, accountability, and the protection of fundamental rights. By embedding these principles into the regulatory framework, the

European Union aims to foster a digital environment that is not only technologically advanced and economically dynamic, but also secure, trustworthy, human-centric, and aligned with democratic values and societal expectations.

The success of this framework will ultimately depend on effective implementation, harmonized enforcement and the ability of public institutions and private organizations to translate regulatory requirements into practical governance mechanisms. Nevertheless, the evidence available in 2026 strongly suggests that the European Union has moved decisively from digital policy design toward digital policy execution through the coordinated implementation of the Data Act, AI Act, Digital Services Act, Digital Identity Framework, cybersecurity legislation and Digital Decade objectives [1] [3] [5] [7] [9] [10].

References

[1] European Commission – *Data Act*. Shaping Europe's Digital Future. Available at: https://digital-strategy.ec.europa.eu/en/policies/data-act

[2] European Commission – *Data Act Explained*. Available at: https://digital-strategy.ec.europa.eu/en/factpages/data-act-explained

[3] Regulation (EU) 2024/1689 of the European Parliament and of the Council laying down harmonised rules on Artificial Intelligence.

[4] European Commission – AI Act implementation timeline and guidance materials.

[5] Regulation (EU) 2022/2065 – Digital Services Act.

[6] European Commission – *Digital Services Act Summary*.

[7] Regulation (EU) 2024/1183 concerning the European Digital Identity Framework.

[8] Commission Implementing Regulation (EU) 2026/798 on European Digital Identity Wallet onboarding requirements.

[9] European Commission – State of the Digital Decade 2026 Report.

[10] Data.europa.eu – Digital Omnibus Update 2026.

[11] NIS2 Directive (EU) 2022/2555.

[12] Cyber Resilience Act (EU).

Bibliography

BELLAMY, C. – *Governing in the Information Age*. Oxford University Press.

CASTELLS, M. – *The Rise of the Network Society*. Wiley-Blackwell.

European Commission – *European Data Strategy*.

European Commission – *Digital Decade Policy Programme 2030*.

European Commission – *Shaping Europe's Digital Future*.

European Parliament – *The Digital Services Act*.

European Parliament – *The Digital Markets Act*.

European Parliament – *The Artificial Intelligence Act*.

ENISA – *Threat Landscape Reports*.

OECD – *Digital Economy Outlook*.

OECD – *Going Digital Project*.

World Bank – *Digital Development Reports*.

NIST – *AI Risk Management Framework*.

European Cybersecurity Agency – *Cybersecurity Certification Frameworks*.

European Commission – *Data Governance Act Resources*.

European Commission – *European Digital Identity Framework*.

European Commission – *Common European Data Spaces*.

European Commission – *Digital Fairness Fitness Check*.

JISOM Journal – Author Guidelines and Journal Information (https://digital-strategy.ec.europa.eu/en/policies/2026-state-digital-decade-package)

EU Digital Omnibus developments (https://eur-lex.europa.eu/eli/reg/2022/2065/oj/eng)

State of the Digital Decade 2026 package (https://eur-lex.europa.eu/EN/legal-content/summary/digital-services-act.html)

MODELING THE FLOW OF RESOURCES IN A BALANCED ECONOMIC SYSTEM: FROM A KEYNESIAN PERSPECTIVE

Carmen Dalina ȚÎRDĂ[1]
Elena Raluca CRISTIAN[2]
Anda Veronica DAN[3]

Abstract

This paper explores the analogy between the dynamic flow of fluids and the movement of resources in an economy. Using concepts inspired by mathematical models of generalized Oldroyd-B fluids, the study attempts to develop a conceptual framework that connects the stability of fluid motion with economic equilibrium. The paper extends this perspective through Keynesian theory, focusing on income, consumption, savings, and investment as interrelated flows that determine macroeconomic balance. The goal is to show that both systems: physical and economic, seek stability through internal adjustments and external pressures. The interdisciplinary comparison contributes to a better understanding of economic equilibrium and highlights the value of mathematical thinking in the interpretation of economic processes.

Keywords: Oldroyd-B fluid, parallel plates, the Keynesian framework, economic system.

JEL Classification: E12, O41, C02.

1. Introduction

The study of equilibrium is central to both physics and economics. In physics, fluid models describe how forces and pressures interact to create balance and motion. In economics, equilibrium represents the stable relationship between production, income, and expenditure. Although these fields appear distant, their underlying mechanisms share a common principle: the continuous adjustment of flows.

The Oldroyd-B model, used in fluid mechanics, examines how materials with both viscous and elastic properties react to pressure and deformation. Similarly, in economics, the flow of income and capital reacts to fiscal and monetary pressures. When the system faces disturbances, such as inflation, unemployment, or external shocks, it tends to establish equilibrium through adjustments in spending, savings, and investment.

This paper proposes a conceptual bridge between these two domains. By interpreting the flow of economic variables through mathematical logic inspired by fluid dynamics, we can better visualize how stability is formed and maintained in an economy. The Keynesian

[1] University Lecturer, PhD at the Romanian American University in Bucharest, email address: carmen.dalia.tirda@rau.ro
[2]Assistant Professor, PhD at the Romanian American University in Bucharest, Romania, email address: elena.raluca.cristian@rau.ro
[3] Assistant Professor, PhD at the Romanian American University in Bucharest, Romania, email address: anda.veronica.dan@rau.ro

model provides the theoretical foundation for this analogy, as it describes how total output, consumption, and investment interact dynamically to determine national income.

2. Mathematical and Conceptual Background

In the Oldroyd-B model, fluid flow depends on several parameters that represent viscosity, elasticity, and external forces. The system is considered stable when small changes in pressure or boundary conditions do not cause large variations in flow. In simple terms, the model explains how a fluid responds to stress while maintaining an overall balance.

If we translate this concept to economics, we can interpret "viscosity" as the resistance of the economy to change factors such as institutional rigidity, regulation, or labor market constraints. "Elasticity" reflects the adaptability of markets and agents: how quickly consumption or investment responds to shifts in income or expectations.

A balanced flow in fluid mechanics corresponds to a stable macroeconomic environment. Just as a fluid seeks a steady state movement between two parallel plates, an economy seeks a level of output and income where total demand equals total supply. Both systems are defined by feedback processes that drive them toward equilibrium.

The flows between parallel plates for different non-newtonian fluids are studied by many authors. In [11]-[20] studied the unsteady unidirectional flow of an Oldroyd-B fluid.

Hayat et al. [1] obtained exact analytical solutions for unsteady flow between parallel plates of an Oldroyd-B fluid. They showed the existence of solution for each of the six problems considered :1) unsteady Couette flow, 2) unsteady flow for a rigid and free boundaries, 3) flow between parallel plates suddenly set in motion with same speed, 4) unsteady Poiseuille flow, 5) unsteady generalized Couette flow and 6) unsteady generalized Couette flow for rigid and free boundaries. They showed the existence of solution for each problem considered for all values of non-Newtonian parameters. They also represented velocity profile for small and large times.

Two types of unsteady unidirectional flows of a generalized Oldroyd-B fluid with fractional derivative are presented in [11]. The velocity distrubutions are determinated by discrete Laplace transform and finite Fouriei sine transform.

In [12]-[13] Is studied the steady unidirectional flow of an Oldroyd 6-constant fluid. In [12] is studied Oldroyd 6-constant fluid, flowing through a channel under the as sumption that the fluid slips on the wall. The analitic solutions for Couette, Poiseuille and generalized Couette flows are found using homotopy analysis method (HAM).

The same method is used in [13], to study the steady flow of Oldroyd 6-constant fluid. To find analytical solutions is used a technique based on homotopy (HAM), is successfully applied to several non-linear problems.

Flow between two parallel plates for a special model of a generalized fluid of complexity two, which includes the Navier-Stokes fluid, power-law fluid, classical second grade-fluid is analyzed in [14]. Here the assumption is that the flow meets Navier slip conditions at the boundary.

For second grade fluids are studied various types of unsteady flows between parallel plates. In [15] are considered the unidirectional flows of a fluid of second grade. These flows are produced by sudden application of a constant pressure gradient or by the impulsive motion of one or two boundaries. The other property of unsteady flows described in

[15] is that the no-slip boundary condition is sufficient for unsteady flows, but for steady flows an additional condition is required.
In [16] are investigated two types of unsteady flow of a second-grade fluid: flow in a duct and flow in a rectangular cross-section. The effects of the side walls on the unsteady flow of such fluid in a duct of rectangular cross-section are considered.
Asghar et al. in [17] considered two problems of unidirectional flow involving second grade fluid with variable material properties. They showed that some exact analytical solutions are possible for unsteady Couette flows of second grade fluid in terms of trigonometric and Chebyshev functions.
In [18] is studied the unsteady motion of inhomogeneous incompressible fluid, where the viscosity varies spatially. Two types of flow are analyzed in this paper, namely: Stokes' second problem and the flow between two parallel plates where one is oscillating.
In this paper the problem of the flow of a generalized Oldroyd -B fluid is studied between two parallel plates. We are interested in knowing if von Karman type solutions are admissible for this fluid. We solve the problem using a power series technique and obtain the velocity field as well as the components for the Cauchy tensor.

1.The flow problem.

The Cauchy stress tensor is given:

$$\mathbf{T} = -p\mathbf{I} + \mathbf{T}_E, \quad \mathbf{T}_E + \lambda \frac{D\mathbf{T}_E}{Dt} = \mu\left(\mathbf{A_1} + \lambda_1 \frac{D\mathbf{A_1}}{Dt}\right), \tag{1.1}$$

where $\mathbf{T}_E$ is the extra-stress tensor (effective stress - tensor), -pI denotes the inde- terminate spherical stress, $\mathbf{A}_1 = \mathbf{L} + \mathbf{L}^T$ is the first Rivlin - Ericksen tensor, L is the velocity gradient, λ and λ_1 are the relaxation times, μ is the dynamic viscosity. The convective derivative of $\mathbf{T}_E$ and $\mathbf{A}_1$ are expressed through:

$$\begin{aligned} \frac{D\mathbf{T}_E}{Dt} &= \dot{\mathbf{T}}_E + \mathbf{T}_E\mathbf{L} + \mathbf{L}^T\mathbf{T}_E, \\ \frac{D\mathbf{A}_1}{Dt} &= \dot{\mathbf{A}}_1 + \mathbf{A}_1\mathbf{L} + \mathbf{L}^T\mathbf{A}_1. \end{aligned} \tag{1.2}$$

The fluid flows between two parallel plates. The upper plate is supposed to be porous, and the fluid passes through with constant vertical velocity, meaning:
$\mathbf{v}(x, y)|_{y=d} = -v_0\mathbf{e}_2$
The other one moves with speed:
$\mathbf{v}(x, y)|_{y=0} = cx\mathbf{e}_1$

where" d" is the distance between the two plates, e_1 and e_2 are the unit vector in the horizontal and respective vertical directions and" c" is a given constant.

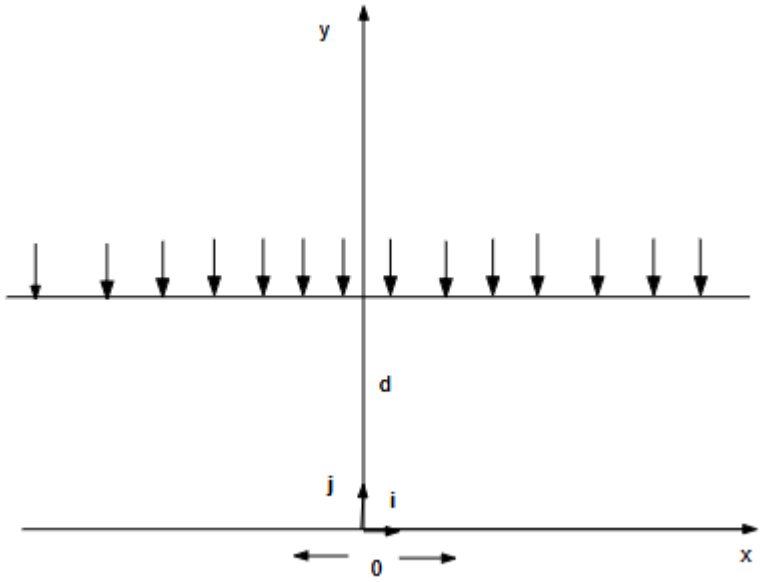


Figure 1: Geometric representation of the flow domain[4].

We are interested in the following problem: does a generalized Oldroyd -B fluid accept a von Karman solution for the flow problem described above? We shall suppose, like in [11], that the admissible velocity field is of von Karman type

$$u = cxf'(\eta),\ v = -cdf(\eta), \qquad (1.3)$$

where $y \equiv d\eta$.
This flow field satisfies the constraint of incompressibility: $div\ \mathrm{v} = 0$.
From the form of velocity field proposed results the acceleration

$$\mathbf{a} = dc^2\overline{x}(f'^2 - ff'')\mathrm{e}_1 + dc^2 ff'\mathrm{e}_2, \qquad (1.4)$$

where $x = x/d$. The local form of the balance of linear momentum:

$$\rho\mathbf{a} = \rho\mathbf{b} + div\mathrm{T}.$$

We assume that the specific body force $\mathrm{b} \equiv 0$. Since the velocity field is independent of z, the stress field will also be independent of z. We can now write the equations of motion in the form

[4] Author's own contribution

$$\rho c^2 \bar{x} d(f'^2 - ff'')\mathbf{e}_1 + \rho c^2 d f f' \mathbf{e}_2 = \frac{1}{d}\left(\frac{\partial T^{11}}{\partial \bar{x}} + \frac{\partial T^{12}}{\partial \eta}\right)\mathbf{e}_1 + \frac{1}{d}\left(\frac{\partial T^{12}}{\partial \bar{x}} + \frac{\partial T^{22}}{\partial \eta}\right)\mathbf{e}_2 +$$
$$+\frac{1}{d}\left(\frac{\partial T^{13}}{\partial \bar{x}} + \frac{\partial T^{23}}{\partial \eta}\right)\mathbf{e}_3. \tag{1.5}$$

The dimensionless form of the equation (1.5)

$$Re\bar{x}(f'^2 - ff'')\mathbf{e}_1 + Reff'\mathbf{e}_2 = \left(\frac{\partial \bar{T}^{11}}{\partial \bar{x}} + \frac{\partial \bar{T}^{12}}{\partial \eta}\right)\mathbf{e}_1 + \left(\frac{\partial \bar{T}^{12}}{\partial \bar{x}} + \frac{\partial \bar{T}^{22}}{\partial \eta}\right)\mathbf{e}_2 +$$
$$+\left(\frac{\partial \bar{T}^{13}}{\partial \bar{x}} + \frac{\partial \bar{T}^{23}}{\partial \eta}\right)\mathbf{e}_3.$$

where $Re = \frac{\rho c d^2}{\mu}$ is the Reynolds number and $\bar{T}^{ij} = \frac{T^{ij}}{\mu c}$ are the dimensionless components of the Cauchy stress tensor.

Considering the expression $(1.1)_1$, we obtain the following system for the equations of motion

$$Re\bar{x}(f'^2 - ff'') = \frac{\partial \bar{T}_E^{11}}{\partial \bar{x}} + \frac{\partial \bar{T}_E^{12}}{\partial \eta} - \frac{\partial \bar{p}}{\partial \bar{x}},$$
$$Reff' = \frac{\partial \bar{T}_E^{12}}{\partial \bar{x}} + \frac{\partial \bar{T}_E^{22}}{\partial \eta} - \frac{\partial p}{\partial \eta}, \tag{1.6}$$
$$\frac{\partial \bar{T}_E^{13}}{\partial \bar{x}} + \frac{\partial \bar{T}_E^{23}}{\partial \eta} = 0.$$

where $\bar{p} = \frac{p}{\mu c}$.

The constitutive equation (1.1) using (1.2) is equivalent to the following system

$$
\begin{aligned}
&2f' - 2c\lambda_1(ff'' - 2f'^2) = \lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{11}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{11}}{\partial \eta} + 2f'\bar{T}_E^{11}\right] + \bar{T}_E^{11},\\
&\frac{x}{d}f'' + c\lambda_1\frac{x}{d}(3f'f'' - ff''') = \lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{12}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{12}}{\partial \eta} + \frac{x}{d}f''\bar{T}_E^{11}\right] + \bar{T}_E^{11},\\
&\lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{13}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{13}}{\partial \eta} + f'\bar{T}_E^{13}\right] + \bar{T}_E^{13} = 0,\\
&-2f' + 2c\lambda_1(ff'' + 2f'^2) = \lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{22}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{22}}{\partial \eta} + 2\frac{x}{d}f''\bar{T}_E^{12} - 2f'\bar{T}_E^{22}\right] + \bar{T}_E^{22},\\
&\lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{23}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{23}}{\partial \eta} + \frac{x}{d}f''\bar{T}_E^{13} - f'\bar{T}_E^{23}\right] + \bar{T}_E^{23} = 0,\\
&\lambda c\left[\frac{x}{d}f'\frac{\partial \bar{T}_E^{33}}{\partial \bar{x}} - f\frac{\partial \bar{T}_E^{33}}{\partial \eta}\right] + \bar{T}_E^{33} = 0.
\end{aligned}
\tag{1.7}
$$

The dimensionless boundary conditions obtained from the mechanical problem described

$$
f(0) = 0, \quad f(1) = \frac{v_0}{cd}, \quad f'(0) = 1, \quad f'(1) = 0. \tag{1.8}
$$

2. The Solution for the equations of motion.

We are looking for a solution to the problem (1.6) -(1.7) -(1.8).
For the components of the effective stress, we make the folowing assumptions

$$
\begin{aligned}
&\bar{T}_E^{13} = \bar{T}_0^{13}(\eta) + \frac{x}{d}\bar{T}_1^{13}(\eta), \quad \bar{T}_E^{23} = \bar{T}_0^{11}(\eta) + \frac{x}{d}\bar{T}_1^{23}(\eta),\\
&\bar{T}_E^{33} = \bar{T}_0^{11}(\eta) + \frac{x}{d}\bar{T}_1^{33}(\eta), \quad \bar{T}_E^{11} = \bar{T}_0^{11}(\eta) + \frac{x}{d}\bar{T}_1^{11}(\eta),\\
&\bar{T}_E^{12} = \bar{T}_0^{12}(\eta) + \frac{x}{d}\bar{T}_1^{12}(\eta), \quad \bar{T}_E^{22} = \bar{T}_0^{22}(\eta) + \frac{x^2}{d^2}\bar{T}_2^{22}(\eta).
\end{aligned}
\tag{2.1}
$$

First, we analyze the system consisting of equations $(1.7)_{3,5,6}$ and $(1.6)_3$.

If we use the assumptions $(2.1)_{1,2,3}$ and identify the coefficients of $\left(\frac{x}{d}\right)^n (n = 0, 1, 2)$, we obtain the following system

$$\lambda c\left[f'\bar{T}_1^{13} - f\frac{d\bar{T}_1^{13}}{d\eta} + f'\bar{T}_1^{13}\right] + \bar{T}_1^{13} = 0, \quad \lambda c\left[-f\frac{d\bar{T}_0^{13}}{d\eta} + f'\bar{T}_0^{13}\right] + \bar{T}_0^{13} = 0,$$

$$c\lambda f''\bar{T}_1^{13} = 0, \quad \lambda c\left[-f\frac{d\bar{T}_1^{23}}{d\eta} + f''\bar{T}_0^{13}\right] + \bar{T}_1^{23} = 0,$$

$$-\lambda c\left[f\frac{d\bar{T}_0^{23}}{d\eta} + f'\bar{T}_0^{23}\right] + \bar{T}_0^{23} = 0, \quad \lambda c\left[f'\bar{T}_1^{33} - f\frac{d\bar{T}_1^{33}}{d\eta}\right] + \bar{T}_1^{33} = 0,$$

$$-\lambda c f\frac{d\bar{T}_0^{33}}{d\eta} + \bar{T}_0^{33} = 0, \quad \frac{d\bar{T}_1^{23}}{d\eta} = 0, \quad \frac{d\bar{T}_0^{23}}{d\eta} + \bar{T}_1^{13} = 0. \tag{2.2}$$

From $(2.2)_3$result $\bar{T}_1^{13} = 0$, ,because the equation $f''' = 0$ has no solutions if we consider the bilocal problem obtained from the described mechanical problem:

$f(0) = 0, f(1) = \frac{v0}{cd}, f'(0) = 1, f'(1) = 0.$ Also obtain that $T^{-23} = 0.$

The components of the effective stress are now expressed as

$$T^{-13} = \bar{T}^{13}(\eta), \; T^{-23} = {}^{x}\bar{T}^{23}(\eta), \; T^{-33} = T^{33}(\eta) + {}^{x}\bar{T}^{33}(\eta).$$

$$\bar{T}_E^{13} = \bar{T}_0^{13}(\eta), \quad \bar{T}_E^{23} = \frac{x}{d}\bar{T}_1^{23}(\eta), \quad \bar{T}_E^{33} = \bar{T}_0^{33}(\eta) + \frac{x}{d}\bar{T}_1^{33}(\eta). \tag{2.3}$$

The system (2.2) is now

$$\lambda c\left[-f\frac{d\bar{T}_0^{13}}{d\eta} + f'\bar{T}_0^{13}\right] + \bar{T}_0^{13} = 0, \quad \lambda c f''\bar{T}_0^{13} + \bar{T}_1^{23} = 0,$$

$$\lambda c\left[f'\bar{T}_1^{33} - f\frac{d\bar{T}_1^{33}}{d\eta}\right] + \bar{T}_1^{33} = 0, \quad -\lambda c f\frac{d\bar{T}_0^{33}}{d\eta} + \bar{T}_0^{33} = 0, \quad \frac{d\bar{T}_1^{23}}{d\eta} = 0. \tag{2.4}$$

Without loss of generality, we can suppose that $T^{-13} = T^{-23} = T^{-33} = 0$ for $\eta = 1$. Using these assumptions, we obtain that

$$\bar{T}_E^{13}(\bar{x}, \eta) = \bar{T}_E^{23}(\bar{x}, \eta) = \bar{T}_E^{33}(\bar{x}, \eta) = 0.$$

Now we use the expressions $(2.1)_{4,5,6}$ in $(1.7)_{1,2,4}$ and we identify the coefficients of $\left(\frac{x}{d}\right)^n$, $(n=0,1,2)$ Thus we obtain the following system for the constitutive equations

$$\lambda\left[3cf'\bar{T}_1^{11}-cf\frac{d\bar{T}_1^{11}}{d\eta}\right]+\bar{T}_1^{11}=0,$$

$$2c\mu f'-2c^2\mu\lambda_1(ff''-2f'^2)=\lambda\left[-cf\frac{d\bar{T}_0^{11}}{d\eta}+2cf'\bar{T}_0^{11}\right]+\bar{T}_0^{11},\quad c\lambda f''\bar{T}_1^{11}=0,$$

$$c\mu f''+c^2\mu\lambda_1(3f'f''-ff''')=\lambda\left[cf'\bar{T}_1^{12}-cf\frac{d\bar{T}_1^{12}}{d\eta}+cf''\bar{T}_0^{11}\right]+\bar{T}_1^{12},$$

$$-\lambda cf\frac{d\bar{T}_0^{12}}{d\eta}+\bar{T}_0^{12}=0,\quad 2c^2\mu\lambda_1 f'^2=\lambda\left[-cf\frac{d\bar{T}_2^{22}}{d\eta}+2cf''\bar{T}_1^{12}\right]+\bar{T}_2^{22},$$

$$2c\lambda f''T_0^{12}=0,\quad -2c\mu f'+2c^2\mu\lambda_1(ff''+2f'^2)=\lambda\left[-cf\frac{d\bar{T}_0^{22}}{d\eta}-2cf'\bar{T}_0^{22}\right]+\bar{T}_0^{22}. \tag{2.5}$$

From $(2.5)_3$ and $(2.5)_7$ result $T^{-11}=0$ and $T^{-12}=0$. We notice that equations $(2.5)_1$ and $(2.5)_5$ are satisfayed. The components of the effective stress are now expressed as

$$\bar{T}_E^{11}=\bar{T}_0^{11}(\eta),\quad \bar{T}_E^{12}=\frac{x}{d}\bar{T}_1^{12}(\eta),\quad \bar{T}_E^{22}=\bar{T}_0^{22}(\eta)+\frac{x^2}{d^2}\bar{T}_2^{22}(\eta). \tag{2.6}$$

The system (2.5) becomes now

$$
\begin{aligned}
&2f' - 2c\lambda_1(ff'' - 2f'^2) = \lambda c\left[-f\frac{d\bar{T}_0^{11}}{d\eta} + 2f'\bar{T}_0^{11}\right] + \bar{T}_0^{11},\\
&f'' + c\lambda_1(3f'f'' - ff''') = \lambda c\left[f'\bar{T}_1^{12} - f\frac{d\bar{T}_1^{12}}{d\eta} + f''\bar{T}_0^{11}\right] + \bar{T}_1^{12},\\
&2c\lambda_1 f''^2 = \lambda c\left[-f\frac{d\bar{T}_2^{22}}{d\eta} + 2f''\bar{T}_1^{12}\right] + \bar{T}_2^{22},\\
&-2f' + 2c\lambda_1(ff'' + 2f'^2) = \lambda c\left[-f\frac{d\bar{T}_0^{22}}{d\eta} - 2f'\bar{T}_0^{22}\right] + \bar{T}_0^{22}.
\end{aligned}
\tag{2.7}
$$

We eliminate the pressure in the system (1.6), and we use (2.6), thus obtaining the following equation

$$
Re(f'f'' - ff''') = \frac{d^2\bar{T}_1^{12}}{d\eta^2} - 2\frac{d\bar{T}_2^{22}}{d\eta}. \tag{2.8}
$$

The problem that we must solve now is (2.7) -(2.8). The unknown functions are: $\mathbf{f}, \bar{T}_1^{12}, \bar{T}_2^{22}, \bar{T}_0^{22}, \bar{T}_0^{11}$.
The boundary conditions for fa re (1.8) and for the components of the effective stress is

$$
\begin{aligned}
&\bar{T}_1^{12}(1) = 2(1 - 3\frac{v_0}{cd}),\\
&\bar{T}_0^{22}(1) = \bar{T}_0^{11}(1) = \bar{T}_2^{22}(1) = 0.
\end{aligned}
\tag{2.9}
$$

We seek the solutions of the system by a double scale asymptotic development. The two parameters that appear in this development are $\beta << 1$ and $re << 1$. We first develop asymptotic compared with β the unknown functions from the system (2.7) − (2.8)

$$
f = \sum_{i=0}^{\infty}\beta^i f_i, \qquad \bar{T}_k^{ij} = \sum_{l=0}^{\infty}\beta^l \bar{T}_{k(1)}^{ij}, \tag{2.10}
$$

where
$\beta \equiv O(c\lambda) = O(c\lambda_1) << 1.$

The system for zero-order approximations in β is

$$\begin{aligned} &2f_0' = \bar{T}^{11}_{0(0)}, \\ &f_0'' = \bar{T}^{12}_{1(0)}, \\ &-2c\mu f_0' = \bar{T}^{22}_{0(0)}, \\ &\bar{T}^{22}_{2(0)} = 0, \\ &Re(f_0' f_0'' - f_0 f_0''') = (\bar{T}^{12}_{1(0)})''. \end{aligned} \tag{2.11}$$

The conditions for approximations $f_0, f_i (i = 1, n)$ are

$$\begin{aligned} &f_0(0) = 0, \quad f_0(1) = \frac{v_0}{cd}, \quad f_0'(0) = 1, \quad f_0'(1) = 0. \\ &f_i(0) = f_i(1) = f_i'(0) = f_i'(1) = 0. \end{aligned} \tag{2.12}$$

We derive twice in $(2.11)_2$ and introduced in $(2.11)_5$ we get the differential equation of order iv for f0

$$f_0^{iv} = Re(f_0' f_0'' - f_0 f_0'''). \tag{2.13}$$

If we make the following developments

$$\begin{aligned} &f_0 = f_{00} + Re f_{01} + \ldots, \\ &\bar{T}^{ij}_{k(l)} = \bar{T}^{ij}_{k(l0)} + Re\bar{T}^{ij}_{k(l1)} + \ldots. \end{aligned} \tag{2.14}$$

Thus, we obtain a seguence of linear problems whose solutions are polynomials in $\eta \in [0, 1]$.

$$
\begin{aligned}
f_{00}^{iv} &= 0, \\
f_{01}^{iv} &= f_{00}' f_{00}'' - f_{00} f_{00}''', \\
f_{02}^{iv} &= f_{00}' f_{01}'' + f_{01}' f_{00}'' - f_{00} f_{01}''' - f_{01} f_{00}''', \\
&\ldots
\end{aligned}
\tag{2.15}
$$

Thus, for the first two approximations of f_0 (in Re) we obtain

$$
\begin{aligned}
f_{00}(\eta) &= A\eta^3 + B\eta^2 + \eta, \\
f_{01}(\eta) &= \frac{A^2}{70}\eta^7 + \frac{AB}{30}\eta^6 + \frac{B^2}{30}\eta^5 + \frac{B}{12}\eta^4 + \\
&+ (-\frac{A^2}{14} - \frac{2AB}{15} - \frac{B^2}{10} - \frac{B}{6})\eta^3 + (\frac{2A^2}{35} + \frac{AB}{10} + \frac{B^2}{15} + \frac{B}{12})\eta^2.
\end{aligned}
\tag{2.16}
$$

With

$$
A = 1 - 2\frac{v_0}{cd}, \quad B = 3\frac{v_0}{cd} - 2, \tag{2.17}
$$

For the approximations we obtain (using $(2.16)_1$) the following formula

$$
\begin{aligned}
\bar{T}_{0(00)}^{11} &= 2(3A\eta^2 + 2B\eta + 1), \\
\bar{T}_{1(00)}^{12} &= 6A\eta + 2B, \\
\bar{T}_{0(00)}^{22} &= -2(3A\eta^2 + 2B\eta + 1),
\end{aligned}
\tag{2.18}
$$

and for $\bar{T}_{k(l1)}^{ij}$ we have (using $(2.16)_2$)

$$\bar{T}^{11}_{0(01)} = 2\left\{\frac{A^2}{10}\eta^6 + \frac{AB}{5}\eta^5 + \frac{B^2}{6}\eta^4 + \frac{B}{3}\eta^3 + 3(-\frac{A^2}{14} - \frac{2AB}{15} - \frac{B^2}{10} - \frac{B}{6})\eta^2 + 2(\frac{2A^2}{35} + \frac{AB}{10} + \frac{B^2}{15} + \frac{B}{12})\eta\right\}.$$

$$\bar{T}^{12}_{1(01)} = \left\{\frac{3A^2}{5}\eta^5 + AB\eta^4 + \frac{2B^2}{3}\eta^3 + B\eta^2 + 6(-\frac{A^2}{14} - \frac{2AB}{15} - \frac{B^2}{10} - \frac{B}{6})\eta + 2(\frac{2A^2}{35} + \frac{AB}{10} + \frac{B^2}{15} + \frac{B}{12})\right\},$$

$$\bar{T}^{22}_{0(01)} = -2\left\{\frac{A^2}{10}\eta^6 + \frac{AB}{5}\eta^5 + \frac{B^2}{6}\eta^4 + \frac{B}{3}\eta^3 + 3(-\frac{A^2}{14} - \frac{2AB}{15} - \frac{B^2}{10} - \frac{B}{6})\eta^2 + 2(\frac{2A^2}{35} + \frac{AB}{10} + \frac{B^2}{15} + \frac{B}{12})\eta\right\},$$

$$\bar{T}^{22}_{2(11)} = 0. \qquad (2.19)$$

For the first-order approximations in beta: f_1 and $\bar{T}^{ij}$ we can show that

$$f_1 \cong f_{10} + Re f_{11} = 0,$$

$$\bar{T}^{ij}_{k(1)} \cong \bar{T}^{ij}_{k(10)} + Re\bar{T}^{ij}_{k(11)} = 0.$$

Consequently, from double scale asymptotic development of the unknown function f

$$f = \sum_{i,j=0}^{n}(f_{ij}\beta^i)Re^j = \sum_{j=0}^{n} f_{0j}Re^j + \beta\sum_{j=0}^{n} f_{1j}Re^j + \ldots = (f_{00} + \beta f_{10}) + (f_{01} + \beta f_{11})Re + \ldots,$$

we make the following approximation

$$f \cong f_{00} + Re f_{01}. \qquad (2.20)$$

Similarly for the dimensionless components of the effective stress we consider

$$\bar{T}_0^{11} \cong \bar{T}_{0(00)}^{11} + Re\bar{T}_{0(01)}^{11}$$

$$\bar{T}_1^{12} \cong \bar{T}_{1(00)}^{12} + Re\bar{T}_{1(01)}^{12},$$

$$\bar{T}_2^{22} \cong 0, \qquad (2.21)$$

$$\bar{T}_0^{22} \cong \bar{T}_{0(00)}^{22} + Re\bar{T}_{0(01)}^{22}.$$

Conclusions. We evaluate the interaction between the fluid and the two plates, that is $\mathbf{Tn} \cdot \mathbf{n}$ and $\mathbf{Tn} \cdot \boldsymbol{\tau}$. If we use $(2.6)_3$

$$T_E^{22} = T_0^{22}(\eta) + \frac{x^2}{d^2} T_2^{22}(\eta),$$

and if we are considering that we find that $\bar{T}_2^{22} \cong 0$ find that

$$\mathbf{Tn} \cdot \mathbf{n} = -\bar{p} + \bar{T}_0^{22}(\eta).$$

Using $(2.6)_3$, $(2.18)_3$ and $(2.19)_3$ we obtain

$$\mathbf{Tn} \cdot \mathbf{n} = -p + \bar{T}_{0(00)}^{22} + Re\bar{T}_{0(01)}^{22} = -\bar{p} - 2\left\{3A\eta^2 + 2B\eta + 1\right.$$

$$+Re\left[\frac{A^2}{10}\eta^6 + \frac{AB}{5}\eta^5 + \frac{B^2}{6}\eta^4 + \frac{B}{3}\eta^3 + 3(-\frac{A^2}{14} - \frac{2AB}{15} - \frac{B^2}{10} - \frac{B}{6})\eta^2\right. \qquad (2.22)$$

$$\left.\left. + 2(\frac{2A^2}{35} + \frac{AB}{10} + \frac{B^2}{15} + \frac{B}{12})\eta\right]\right\}.$$

where A and B are given by (2.17). A simple calculus gives the force on the two plates. That is for normal forces

$$\mathbf{Tn} \cdot \mathbf{n}\,|_{\eta=0} = -\bar{p} - 2,$$

$$\mathbf{Tn} \cdot \mathbf{n}\,|_{\eta=1} = -\bar{p} - 2(3A + 2B + 1). \qquad (2.23)$$

It is easy to see that if $\frac{v0}{cd} = \frac{1}{2}$

$$(\mathbf{Tn}\cdot\mathbf{n}\mid_{\eta=0}+\bar{p})=-2,$$

$$(\mathbf{Tn}\cdot\mathbf{n}\mid_{\eta=1}+\bar{p})=0.$$

Using (2.6) and (2.21) we have

$$\bar{T}^{11}+\bar{p}\equiv\bar{T}_E{}^{11}=\bar{T}_0{}^{11}(\eta)=\bar{T}^{11}_{0(00)}+Re\bar{T}^{11}_{0(01)},$$

$$\bar{T}^{12}+\bar{p}\equiv\bar{T}_E{}^{12}=\frac{x}{d}\bar{T}_1{}^{12}(\eta)=\frac{x}{d}(\bar{T}^{12}_{1(00)}+Re\bar{T}^{12}_{1(01)}).$$

Thus, we obtain the dimensionless components of the effective stress

$$\begin{aligned}
\bar{T}^{11}_E &= 2(3A\eta^2+2B\eta+1)+2Re\left\{\frac{A^2}{10}\eta^6+\frac{AB}{5}\eta^5+\frac{B^2}{6}\eta^4+\frac{B}{3}\eta^3+\right.\\
&\left.+3(-\frac{A^2}{14}-\frac{2AB}{15}-\frac{B^2}{10}-\frac{B}{6})\eta^2+2(\frac{2A^2}{35}+\frac{AB}{10}+\frac{B^2}{15}+\frac{B}{12})\eta\right\},\\
\bar{T}^{12}_E &= \frac{x}{d}\left\{6A\eta+2B+Re\left[\frac{3A^2}{5}\eta^5+AB\eta^4+\frac{2B^2}{3}\eta^3+B\eta^2+\right.\right.\\
&\left.\left.+6(-\frac{A^2}{14}-\frac{2AB}{15}-\frac{B^2}{10}-\frac{B}{6})\eta+2(\frac{2A^2}{35}+\frac{AB}{10}+\frac{B^2}{15}+\frac{B}{12})\right]\right\}.
\end{aligned}\tag{2.24}$$

3. The Keynesian Framework

Keynesian economics is built upon the idea that total income in an economy (Y) equals the sum of consumption (C), investment (I), government spending (G), and net exports (NX): Y = C + I + G + NX.

Each of these components represents a flow of resources. Income flows from firms to households; consumption flows from households back to firms; savings become the source of future investments; and government and trade activities act as external currents influencing the balance.

According to Keynes, equilibrium occurs when aggregate demand equals aggregate supply. However, the process is dynamic rather than static. If consumption increases faster than production, inflationary pressures emerge. If investment declines, unemployment may rise. The system continuously adjusts much like a fluid adjusting to new pressure gradients.

In this sense, we can view the Keynesian multiplier as an "elastic coefficient" that measures how changes in spending propagate through the economy. A high multiplier means that small changes in investment can produce large variations in total income, like how a low-viscosity fluid responds strongly to small forces.

The stability of equilibrium depends on the relationship between these flows. Excessive rigidity in consumption or savings behavior can slow recovery, while high adaptability

enhances resilience. Therefore, the economic system: like a physical one, requires a balance between flexibility and structure.

Keynesian economics emphasizes that equilibrium in an economy is not a static condition but a continuous process of adjustment. When total spending (aggregate demand) equals total output (aggregate supply), the economy operates at its potential level. However, in real life, disturbances such as changes in consumer confidence, government policy, or global trade can shift these flows and move the system away from equilibrium.

Keynes identified consumption (C) and investment (I) as the two primary forces determining total income (Y). Consumption depends largely on disposable income and psychological factors influencing people's willingness to spend. Investment, on the other hand, depends on interest rates and the expected return on capital. When interest rates fall, investments tend to rise, stimulating production and income.

Savings (S) play a crucial role in this process. While savings provide the funds needed for investment, excessive savings can reduce demand, leading to stagnation, a concept Keynes referred to as the paradox of thrift. Maintaining equilibrium thus requires a balance between saving and spending, which can be influenced by fiscal policy (taxation and government expenditure) and monetary policy (control of money supply and interest rates).

This framework mirrors physical systems where the flow of forces and responses determines balance. Just as fluid pressure can be adjusted to restore stability, fiscal and monetary instruments can be used to correct economic imbalances. The objective of economic policy is therefore like the stabilization of a dynamic system: to reduce oscillations and guide the economy toward steady growth.

4. Integrating the Two Models

The analogy between fluid dynamics and economic equilibrium is not purely metaphorical. Both systems can be modeled through equations describing rates of change and feedback mechanisms. In the Oldroyd-B context, stress and strain rates define how energy is distributed within the system. In economics, similar interactions occur between production, income, and expenditure.

For example, when investment levels change, they create "pressure differentials" in income distribution and demand. These differentials trigger flows of adjustment: in wages, prices, and resource allocation, until a new equilibrium is achieved. A resistant economy, with high institutional viscosity, will adjust slowly, while a flexible one will stabilize faster.

By combining the structural insights of mathematics with the behavioral focus of Keynesian theory, this framework allows us to reinterpret economic equilibrium not as a fixed point but as a process of continuous motion. Stability emerges from constant adjustments, where opposing forces, spending and saving, investment and consumption; balance each other through dynamic flow.

This interdisciplinary approach highlights how economic systems can be studied using simplified versions of physical models, improving our understanding of how shocks propagate and how resilience can be enhanced through policy design.

5. Conclusions

The comparison between fluid flow and economic equilibrium reveals that both disciplines share a fundamental logic: systems strive for balance through the adjustment of internal

flows. The Oldroyd-B model offers a mathematical metaphor for the behavior of macroeconomic variables, while Keynesian theory provides the economic meaning of those movements.

Viewing the economy as a dynamic system of interacting flows helps policymakers and researchers understand the importance of adaptability, coordination, and stability. Just as viscosity and elasticity determine whether fluid remains stable or turbulent, structural and behavioral factors determine whether an economy sustains growth or falls into crisis.

This interdisciplinary framework opens future directions for research, such as modeling capital mobility, digital resource flows, or policy transmission mechanisms, using mathematical reasoning inspired by the physical sciences.

This study proposed a conceptual analogy between the flow of resources in an economy and the flow of matter in a physical system. Through this comparison, it becomes clear that equilibrium: whether physical or economic, is not a fixed point but a state of dynamic balance maintained through continuous adjustments.

In the Keynesian framework, equilibrium is sustained by the interdependence of income, consumption, savings, and investment. When one of these components' changes, others must adapt to restore balance. Similarly, in fluid dynamics, any change in pressure or force generates compensatory movements that stabilize the system.

Understanding economic equilibrium as a process of motion rather than rest can help policymakers design more adaptive and flexible strategies. Instead of seeking perfect stability, economies should aim for resilient equilibrium, the ability to absorb shocks and return to sustainable growth without major distortions.

Moreover, the integration of mathematical reasoning, even at a conceptual level, offers a structured way to model how policies propagate through an economy. This interdisciplinary approach combining mathematical modeling and economic theory can support better decision-making in areas such as fiscal sustainability, financial stability, and digital transformation.

In conclusion, both economists and mathematicians share a common goal: to understand how systems respond to change. By studying these flows, we learn that equilibrium is not an absence of movement but the harmony of opposing forces.

References

[1] Keynes, J.M. — *The General Theory of Employment, Interest and Money.* Macmillan. 1936.

[2] Schwab, K. — *The Fourth Industrial Revolution.* World Economic Forum. 2016.

[3] Brynjolfsson, E.; McAfee, A. — *The Second Machine Age.* W.W. Norton & Company. 2014.

[4] Miao, F.; Holmes, W.; et al. — *Artificial Intelligence and Education: Guidance for Policymakers.* UNESCO Publishing. 2021.

[5] OECD — *The Digital Transformation of Education: Connecting Schools, Empowering Learners.* OECD Publishing. 2021.

[6] Tapscott, D. — *The Digital Economy: Rethinking Promise and Peril in the Age of Networked Intelligence.* McGraw-Hill. 2014.

[7] World Bank Group — *Digital Transformation in Romania: Country Diagnostic.* 2022.

[8] UNCTAD — *Technology and Innovation Report 2021: Catching Technological Waves – Innovation with Equity.* United Nations. 2021.

[9] Eurostat — *Digital Economy and Society Statistics – Households and Individuals.* Brussels. 2023.

[10] Hicks, J.R. - *Value and Capital: An Inquiry into Some Fundamental Principles of Economic Theory.* Oxford University Press. 1946.

[11] Haitao, Q.; Minguyu Y.X. — *Some Unsteady Unidirectional Flows of a Generalized Oldroyd-B Fluid with Fractional Derivative. Applied Mathematical Modelling,* 33, pp. 4184–4191. 2009.

[12] Hayat, T.; Khan, M.; Ayub, M. — *On Non-Linear Flows with Boundary Condition. ZAMP,* 56, pp. 1012–1029. 2005.

[13] Hayat, T.; Khan, M.; Ayub, M. — *On the Explicit Analytic Solutions of an Oldroyd 6-Constant Fluid. International Journal of Engineering Science,* 42, pp. 123–135. 2004.

[14] Hron, J.; Le Roux, C.; Malek, J.; Rajagopal, K.R. — *Flows of Incompressible Fluids Subject to Navier's Slip on the Boundary. Computers and Mathematics with Applications,* 56, pp. 2128–2143. 2008.

[15] Erdogan, M.E.; Imrak, C.E. — *On Unsteady Unidirectional Flows of a Second-Grade Fluid. International Journal of Non-Linear Mechanics,* 40, pp. 1238–1251. 2005.

[16] Erdogan, M.E.; Imrak, C.E. — *Effects of the Side Walls on the Unsteady Flow of a Second-Grade Fluid in a Duct of Uniform Cross-Section. International Journal of Non-Linear Mechanics,* 39, pp. 1379–1384. 2004.

[17] Asghar, S.; Hayat, T.; Ariel, P.D. — *Unsteady Couette Flows in a Second-Grade Fluid with Variable Material Properties. Communications in Nonlinear Science and Numerical Simulation,* 14, pp. 154–159. 2009.

[18] Massoudi, M.; Vaidya, A. — *Unsteady Flows of Inhomogeneous Incompressible Fluids. International Journal of Non-Linear Mechanics,* doi:10.1016/j.ijnonlinmec.2011.02.006. 2011.

[19] Verma, V.D.; Singh, R.; Sharma, R. — *Ind. J. Tech,* 24, pp. 557–564. 1986.

[20] Hayat, T.; Khan, M.; Ayub, M. - *Exact Solutions of flow problems of an Oldroyd-B Fluid, Applied Mathematics and Computation,151, pp.105-119,*2004.

[21] Oldroyd, J.G. — *On the Formulation of Rheological Equations of State. Proceedings of the Royal Society of London A,* 200, pp. 523–541. 1950.

[22] Samuelson, P.A. — *Foundations of Economic Analysis.* Harvard University Press. 1947.

[23] Harrod, R.F. — *An Essay in Dynamic Theory. The Economic Journal.* March 1939.

Bibliography

Ahuja, H.L. - *Modern Economics: Micro and Macroeconomics Theory and Applications.* Sultan Chand & Sons. 2020.

Akerman, J. -*Theory of Economic Policy.* London Macmillan. 1969.

Arntz, M.; Gregory, T.; Zierahn, U. — *The Risk of Automation for Jobs in OECD Countries.* OECD. 2016.

Brynjolfsson, E.; McAfee, A. — *The Second Machine Age.* W.W. Norton & Company. 2014.

European Commission — *Digital Education Action Plan 2021–2027.* Brussels. 2021.

Harrod, R.F. — *An Essay in Dynamic Theory. The Economic Journal.* March 1939.

Hicks, J.R. - *Value and Capital: An Inquiry into Some Fundamental Principles of Economic Theory.* Oxford University Press. 1946.

Keynes, J.M. — *The General Theory of Employment, Interest and Money.* Macmillan. 1936.

OECD — *The Digital Transformation of Education: Connecting Schools, Empowering Learners.* OECD Publishing. 2021.

Samuelson, P.A. - *Foundations of Economic Analysis.* Harvard University Press. 1947.

Schwab, K. — *The Fourth Industrial Revolution.* World Economic Forum. 2016.

Tapscott, D. — *The Digital Economy: Rethinking Promise and Peril in the Age of Networked Intelligence.* McGraw-Hill. 2014.

UNCTAD — *Technology and Innovation Report 2021: Catching Technological Waves* –

Innovation with Equity. United Nations. 2021.

World Bank Group — *Digital Transformation in Romania: Country Diagnostic.* 2022.

Online sources (alphabetical order):

https://ec.europa.eu/eurostat — Eurostat official website. Accessed 13-10-2025.
https://digital-strategy.ec.europa.eu — Digital Skills & Jobs Platform (European Commission). Accessed 12-10-2025.
https://www.weforum.org — World Economic Forum official website. Accessed 12-10-2025.

ARTISTICALLY ENHANCED IMAGES: A STUDY ON ACCESSIBILITY AND CREATIVE STYLE IN VIDEO GAMES

Mihai-Lucian VONCILĂ[1]
Eren MURAT[2]
Dragoș-Bogdan TUDOR[3]
Ioan-Lică MARIN[4]
Mihai UDUBAȘA[5]
Oana Irina TURCU[6]
Nicolae TARBĂ[7]
Costin-Anton BOIANGIU[8]

Abstract

This paper presents a novel approach to postprocessing video games by integrating accessibility enhancements for individuals with various types of color blindness (deuteranopia, protanopia, and tritanopia) and vision deficiencies while simultaneously enabling artistically inspired visual transformations. By leveraging real-time shader modifications and advanced image processing techniques, the solution ensures improved color perception, smart edge highlighting, and consistent multi-frame style rendering. The proposed framework addresses the gap between user-centric accessibility optimizations and creative customization in gaming, aiming to broaden both the inclusivity and the aesthetic range of interactive entertainment experiences

Keywords: Accessibility, Color Blindness, Deuteranopia, Protanopia, Tritanopia, Postprocessing Shaders, Artistic Style Transfer, Edge Enhancement, Real-Time Rendering, Video Game Graphics

JEL Classification: D83, L86, I15, O33

[1] PhD Stud., Eng., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, mihai_lucian.voncila@stud.acs.upb.ro
[2] Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, eren.murat@stud.acs.upb.ro
3 Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, dragos_bogdan.tudor@stud.acs.upb.ro
[4] Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, ioan_lica.marin@stud.fsa.upb.ro
[5] Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, mihai.ududbasa@upb.ro
[6] Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, oana_irina.turcu@stud.fsa.upb.ro
[7] PhD Stud., Eng., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, nicolae.tarba@upb.ro
[8] Prof., PhD., Eng., Faculty of Automatic Control and Computers, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania, costin.boiangiu@cs.pub.ro

1. Introduction

One of the main visual impairments that affect people playing video games is color blindness. This color deficiency affects approximately up to 8% of the male population, and 0.5% of the females [1], with the most common being forms of deuteranopia and protanopia. This impairment makes it hard to view certain important elements that would lead to finishing important tasks, such as health bars, quest markers, or team colors.

Thus, one of the main challenges that game developers face is that of having to balance player experience alongside graphic fidelity, and performance to cater to the various needs of many people in regard to accessibility. It has been shown that standard visuals often fail to accommodate those with color vision deficiencies or low-contrast perception [1, 2].

Thus, it is important to provide such people with aid in recognizing certain visual cues. That being said, research shows that even subtle changes in hue, saturation, or luminance can significantly change gameplay clarity [1], making the task of providing such benefits in these scenarios even more challenging. Similarly, there is a need to use other techniques, such as edge enhancement in order to accommodate other forms of visual impairment [3].

On a more whimsical note, there is also the desire to magically shift the visual aesthetic of a game into something reminiscent of a famous artist's style, with the end goal being the expansion of inclusivity and delight in modern video games.

In order to address both the accessibility issue and the performance issues, developers can integrate various changes at different points in their rendering pipeline, without having a major impact on the overall performance of the game [1, 4, 5]. Recent research has implemented shader-based solutions that adapt color palettes, highlight edges, and even add contextual outlines for improved object differentiation, showcasing that player satisfaction is maximized when accessibility is a problem that is tackled from the start rather than later [6].

While many accessibility-driven modifications stay close to the original aesthetic of a game, there is a growing trend of creative re-skinning, where entire scenes are transformed to emulate specific art styles [7, 8]. Pioneering work in image style transfer, particularly the neural style transfer approach introduced by Gatys et al. [9], has paved the way for real-time stylization in gaming contexts [8].

Of course, retexturing entire worlds with various styles can introduce performance overhead. Other works on real-time rendering describe how dynamic load balancing and pipeline optimization such as shader execution reordering help maintain stable frame rates even under heavy workloads [10]. In addition, research on interactive evolutionary computation has demonstrated that procedural shader generation can enable non-experts to create visually appealing results [11].

Finally, deep learning–based frame interpolation methods have been verified in studies such as Bao et al.'s DAIN (Depth-Aware video frame Interpolation) [12] and Mengistu [13], which together confirm that generating intermediate frames via optical flow and convolutional autoencoders can effectively boost apparent frame rates while preserving image quality. Together, these findings support the view that combining advanced load balancing, shader optimization, and deep learning interpolation not only elevates gaming's visual appeal but also enhances functional clarity and responsiveness for a diverse audience.

In this paper, we present two different techniques that try to address these accessibility issues. First directly at the pipeline level, by using color correction shaders, and enhancing edges, and secondly in the Unreal Engine 5, by combining this approach with post-processing volumes, and a variety of filters to test performance impacts.

2. Literature Review

This section provides an overview of existing research and methodologies relevant to accessibility-focused rendering and artistic style transfer in video games.

2.1. Color Blindness

Deuteranopia, Protanopia, and Tritanopia are three forms of color vision deficiencies (commonly referred to as "color blindness") that result from the reduced or absent function of specific cone cells in the retina.

A widely adopted solution is to apply color transformation matrices based on the specific type of color blindness being addressed. These matrices can be incorporated directly into pixel shaders. A general approach for modifying the color vector Cin to produce color-blind-friendly output Cout is to employ the accurate Mcb generated based on the target deficiency (e.g., protanopia, deuteranopia, tritanopia). According to [1], the computational overhead for such matrix multiplications remains minimal, especially with modern GPU pipelines [4].

In addition to static matrices, dynamic adjustments can be provided so that users may tweak brightness, contrast, or even saturation to better suit their preferences. Our demonstrator application employs a set of user-facing parameters (e.g., slider bars for hue rotation) to ensure seamless real-time color adjustments, making the game experience more inclusive [6].

2.2. Major Visual Impairments

Though color blindness tends to be one of the most common disability issues when talking about visual impairment, it is not the only one that needs to be addressed, as other more severe forms of impairment require a more in-depth implementation in order to properly address them. In recent years, a multitude of papers have dealt with the idea of addressing accessibility issues, in the case of visually impaired people, mostly through audio and haptic feedback [14-19].

Even though all these solutions are beneficial and are of use for people suffering from visual impairments, due to the technology still emerging, and the fact that the vast majority of people wouldn't have access to it, we chose a more accessible approach and tried to address issues at the graphics pipeline.

2.3. Edge Enhancement Techniques for Visual Clarity

Visual clarity is not merely a function of color fidelity. Many players with partial vision or age-related conditions benefit from enhanced edges and outlines that better delineate in-game objects [1, 2]. Such techniques often draw on well-known image processing algorithms, sometimes reimagined and optimized for real-time rendering in shader code [4].

2.3.1. Edge Detection Operations

Classic filters such as the Sobel and Laplacian operators are integral to many shader-based edge detection routines:

$$\nabla I=\sqrt{\left(\frac{\partial I}{\partial x}\right)^2+\left(\frac{\partial I}{\partial y}\right)^2} \tag{1}$$

where $\partial I/\partial x$ and $\partial I/\partial y$ represent partial derivatives of the image I in the x and y directions, respectively. Papers [2, 4] highlight that GPU-based edge detection requires optimizing the kernel computations to avoid excessive pixel-by-pixel overhead.

2.3.2. Shader-Based Outlining and Depth Cues

Contour-based methods can be combined with in-depth information to accentuate important gameplay elements, particularly those in the foreground. An example technique might use a depth-aware Sobel operator:

$$\text{EdgeStrength}=\alpha\times\nabla I+\beta\times\nabla Z \tag{2}$$

where ∇I is the color gradient and ∇Z is the gradient of the depth buffer, with α and β weighting their contributions [1, 2]. By blending color-based and depth-based edges, developers can produce more robust outlines that remain visible even under complex lighting conditions [3].

2.4. Artistic Style Transfer in Real-Time Rendering

While the forays into accessibility improvements often concentrate on color correction and edge detection, contemporary developments also venture into creatively transforming the game's aesthetic. Inspired by seminal work in image style transfer, developers can now emulate the styles of renowned artists, sometimes even combining accessibility layers with these transformations [7, 8].

2.4.1. Neural Style Transfer Foundations

Gatys et al. [9] introduced the concept of neural style transfer, where a style image's aesthetic is extracted via feature correlations (Gram matrices) at certain convolutional layers in a deep neural network. Chen et al. [8] extended this to ensure multi-frame consistency, which is vital in video games where rapid scene changes can cause distracting flicker.

At the heart of neural style transfer lies the concept of comparing style representations (gram matrices) between a style image and the in-game frame [9]. The style loss function can be expressed as:

$$L_{style}(a,x)=\sum_{l\in L} w_l \frac{1}{4N_l^2 M_l^2} \sum_{i,j} \left(G_{ij}^l(x)-G_{ij}^l(a)\right)^2 \quad (3)$$

where G^l is the Gram matrix at layer l, and a and x refer to the style and output image representations, respectively [3, 6]. By carefully selecting layers l and weights wl, real-time frameworks can generate consistent multi-frame style transformations, thus ensuring that a player's journey looks visually cohesive [9].

Performance optimization strategies, such as streamlined network architectures or partial GPU computation, are vital to maintaining real-time frame rates [9, 11].

In the case of multi-style frame consistency, Ruder et al. [7] emphasize that ensuring consistency from one frame to the next requires tracking the style transformation across time. This can be done by retaining partial style information in a recurrent buffer or via motion vectors. The outcome represents a visually cohesive experience.

3. Proposed Method

In this section, we will describe the proposed algorithms, which are split into two different frameworks. Firstly, we have an algorithm that is applied at the shader level in order to perform color corrections and enhance edges. Secondly, the method is expanded in combination with a filtering approach that is designed to be used in the Unreal 5 Engine.

3.1 Shader-Based Color Correction and Edge Enhancement

3.1.1. Algorithm

The first method we propose uses a combination of edge detection, color filtering for common color deficiencies, and a specialized anti-aliasing method called Directionally Localized Anti-Aliasing (DLAA) [20] to reduce flicker and refine object boundaries. Our method is implemented using ReShade [21], a tool that overlays custom shader passes on modern graphics APIs (DirectX, Vulkan, OpenGL). Processing occurs at the end of the render pipeline so it can capture the full scene, including textures, depth buffers, and final color buffers, without significant modification to the underlying application

The first step in our algorithm is correcting color deficiencies. This is performed by reading colors from the back buffer followed by simulating different types of color deficiencies based on a selection.

Next, we compute normals for various pixels in the scene. This is performed in order to aid with detecting edges at further steps. This calculation can be summarized as:

$$N=(\|(Vc-Vn)\times(Vc-Ve)\|,d) \tag{4}$$

where d is the depth of the current texel, Vc is the pixel, while Vn, and Ve represent the top and right neighbors of said pixel.

Separately, the algorithm computes a sum of local depths, and local normals based on all the neighbors of the current texel. Based on these computations, it tries to identify edge pixels. A pixel is classified as an edge if both its depth sum and its normal sum exceed user-defined thresholds. This strategy captures sharp transitions in-depth and normals while also allowing adjustable tolerance levels. Detected edge pixels are marked with specific colors.

Once edges are identified, two distinct sources of boundary information can occur: actual geometric edges in 3D space and color-based edges arising from abrupt changes in the color buffer. Both of these need to be addressed in order to provide an appropriate result.

Firstly, we aim to address abrupt color changes in the image. At this stage, we apply a pre-filter to the detected edges, in order to identify potential abrupt shifts in colors when

transitioning from an object to its edge. These abrupt changes are marked and sent to the DLAA method in order to determine how much to smooth out each edge.

Secondly, we identify potential texture zones existing in the scene that contain strong colors, or in other words either a high contrast or high brightness. These zones are similarly marked, as before, and sent to another DLAA processing step in order to deal with them appropriately.

Finally, the original image is blended with the recomputed textures, based on different user-specified parameters that mix the image using various alpha values for transparency, and other settings related to drawing the edge values. These parameters are used, because testing shows that packed scenes can become overloaded with detected edges, such as those containing foliages, or densely grouped objects.

3.1.2 Visual Results

Figure 1 illustrates the raw edge detection result applied to a 3D scene. At this stage, the algorithm marks strong geometric or color boundaries by examining depth differences and pixel gradients. The benefit is that critical scene outlines become more visible, aiding users

who struggle with object delineation. Similarly, the edges alone could be used in aiding visually impaired people, without the need for other elements being overlapped later.

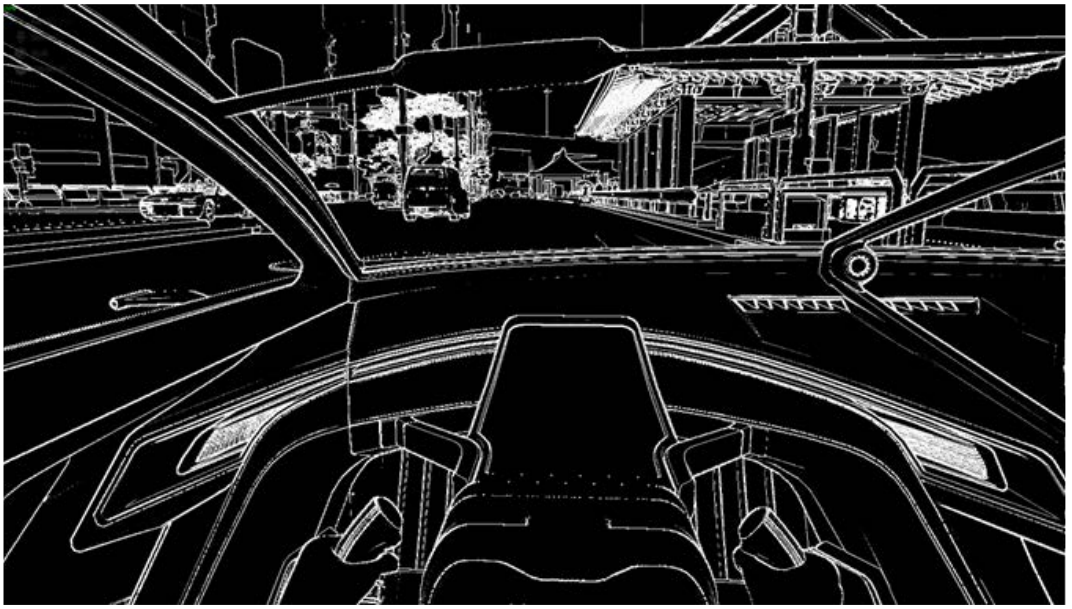


Figure 1. The illuststrative process of edge detection in a video game scene

Figure 2 shows the edge detection overlay superimposed on the original scene. This reveals how the newly generated outlines fit into the existing visuals, and the potential improvements to object perception.

Figure 2. Overlapping the edge detection results in the original video game frame

Figure 3 displays the refined edge detection once the alpha parameter has been integrated. By tuning the opacity of the edge overlay, visually busy areas do not become overwhelming, striking a better balance between highlighting boundaries and maintaining scene readability.

Figure 3. Overlapping the edge detection results in the original video game frame

Figure 4 demonstrates the DLAA filter layered on top of the edge detection effect. This additional step removes flickering or overly sharp edges caused by 2D textures on flat surfaces. The benefit is smoother outlines and reduced artifacts, creating a more cohesive and visually comfortable scene for players.

Figure 4. Overlapping the edge detection results in the original video game frame

Figure 5 displays the result of a simulated deuteranopia filter on a video game frame, alongside its applied correction of the simulated filter. More visual information becomes

available for a deuteranopia-suffering person, especially in the blue haze surrounding the distant city.

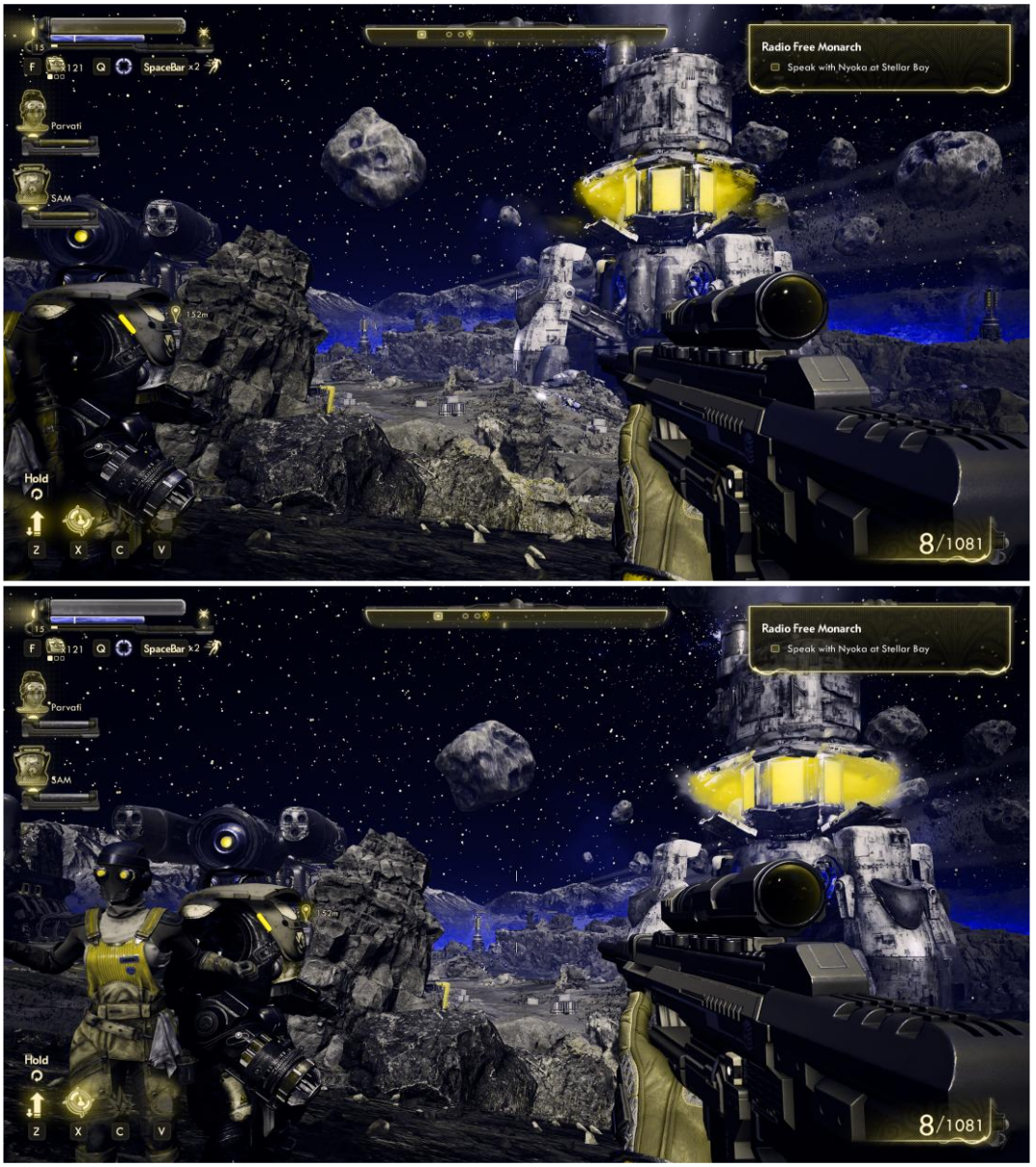


Figure 5. Deuteranopia filter: original (top), corrected (bottom)

The above figures showcase some of the improvements, such as edges in scenes becoming clearer, and certain difficult-to-distinguish objects (like a 2D fish texture rendered on a flat quad) becoming more visibly outlined after applying DLAA. Users with color blindness can enable and calibrate color filters to make critical gameplay elements easier to see, while

users with partial sight can rely on edge detection and anti-aliasing to reduce visual confusion. In summary, the method underscores that combining tolerance-based depth-edge detection with color perception filters and DLAA yields a practical, minimal-overhead strategy to improve visual clarity. By incorporating these strategies in a modular way, small development teams can feasibly enhance accessibility without diverting excessive resources from core game features.

3.2. Shader-Based Color Correction and Edge Enhancement

Our second approach involves changing the image style of certain frames using Unreal Engine 5, more specifically some of its post-process materials [22], and a custom cel-shading setup [23], allowing developers to achieve a certain stylized aesthetic.

3.2.1. Style Transfer Benefits

Even though there aren't many studies that would support the claim that changing the overall style of an image would be beneficial for people suffering from visual impairments, it can be argued that certain styles would be more appropriate in certain scenarios compared to others. Similarly, when people tend to design games for the visually impaired, they tend to make them less complex, in order to accommodate them [6], while this technique would allow for designing a variety of games without compromising.

First of all, changing the visual style in an image can lead to a reduction in overall visual clutter, especially in images that contain photorealistic details, which would be either overwhelming or simply not understood by people with visual impairments, helping them to better focus on certain key elements without needing to worry about understanding certain background elements.

Secondly, changing the artistic style can also lead to better contrast in certain areas of an image, which is something that has been proven to work [6], and that we also employ in our first shader method.

Another argument to be had is that simplifying certain visual elements by altering the overall style of a scene can lead to better consistency in some of the key elements, such as enemies, hazards, or other aspects of gameplay that would lead to a richer overall experience.

3.2.2. Proposed Styles and Filters

Our method mainly involves placing a post-process volume in an Unreal Engine 5 scene, followed by applying the original shader implementation described in Section 3.1, with

small alterations, such as varying DLAA, not including it, or not overlapping edges, combined with optionally applying some post-processing filters at the end of the pipeline.

One such filter, that can be optionally applied is a Kuwahara filter [24], which can be observed in Figure 6. Conceptually, each pixel is examined within a local window divided into four overlapping subregions. Each subregion's variance is computed, and the output color is sampled from the subregion of lowest variance, yielding an intentionally painterly or smudged effect. Symbolically:

$$C_{K(p)} = \min_{\Omega_i \in N(p)} \left(\mathrm{Var}(\Omega_i) \right) \tag{5}$$

where Ω_i are the subregions in the window N(p) centered on pixel p. Although originally meant for noise reduction, the method inverts that concept to stylize each frame by blending pixel values from the smoothest local subregion. Setting a small window size, usually less than 3, helps induce a slightly wavy line effect reminiscent of hand-drawn art.

Figure 6. Kuwahara Filter example

Another approach would be one that is only applied for certain areas of the image, such as shaded, or low brightness ones, for which we can apply a Hatching filter. In this case, after edge detection, we apply a threshold to the lighting buffer, applying the style to shades appearing only under a certain brightness level, as seen in Figure 7.

Figure 7. Hatching Filter example

Figure 8 showcases a look that is meant to mimic an older retro style and is built on top of both pixelation and monochrome techniques. A fog effect is introduced by sampling the depth buffer so that pixels that are farther from the camera trend toward a neutral (often grayish or white) fog color:

$$C_{final} = (1\text{-}F) \times C_{mono\text{-}pixel} + F \times C_{fog} \quad (6)$$

Where $C_{mono\text{-}pixel}$ is the pixelated monochrome color, C_{fog} is the fog tint, and F is a function of distance from the camera. Typically, F increases with depth, creating that characteristic low-visibility effect in distant objects.

Figure 8. Retro Filter example

The Moebius look and feel style, applied to the scene in Figure 10, with results seen in Figure 11, which was inspired by Jean "Moebius" Giraud's fluid linework and flattened color palettes, involves two core elements: stylized color, which is meant to make the scene have a flat, banded shading style, and outline effect, where edges are better outlined, similar to the Hatching Shader approach. A subtle Kuwahara filter, with a small window size, can then inject a slight wobble in the edges, mimicking hand-drawn imperfections.

Figure 9. Retro Filter example

Figure 10. Retro Filter example

For this paper, these techniques are integrated using a post-process volume placed within the scene, allowing the rendering pipeline to apply these transformations just before the image is finalized. Because it operates at the end of the pipeline, the underlying assets (meshes, textures, lighting) remain unaltered, thus preserving the standard production workflow for pre-made or Marketplace assets.

By comparing performance metrics with and without these post-process steps, only minimal frame rate and latency costs were observed, a roughly 5% decrease in frames per second, with no statistically significant change in average latency. This confirms that advanced stylization can be practically integrated into a modern engine. Thanks to the modular nature of Material Instances, developers can fine-tune threshold values or color quantization intervals and quickly iterate on an artistic vision.

4. Conclusions

4.1. Summary of Findings

Our paper addresses two different facets of video game rendering: accessibility for color-blind or low-vision players and creative consistent multi-style frame rendering. Through our integrated shader pipeline, which carefully combined real-time color correction, edge enhancement, and artistic transformations, we found that real-time GPU strategies can meet both goals without severely impacting performance.

Based on the comparative performance results, the artistic post-processing techniques required to achieve the Moebius-inspired look caused only a minor reduction in average FPS (from 110 to 105) and 1% lows (from 100 to 95), indicating a small, acceptable overhead. Crucially, latency remained effectively unchanged, suggesting that the visual enhancements can be integrated without substantially affecting the responsiveness of the game experience.

The tests were performed using the following hardware specifications: (OS) Windows 11 23H2 (CPU) Ryzen 9 7900 (GPU) Radeon RX 6700 XT (RAM) 64GB DDR5@6000MHz.

4.2. Future Directions and Expanding the Framework

Some of the future directions that can be achieved for our framework could include:

- Extending to other more aggravated forms of visual impairment, such as blindness, and its variations that are not properly addressed in the current approach.
- Offering options for dynamic font resizing: This can be done either for people suffering from dyslexia or simply for people with reading issues in general.

- Multi-Platform & VR approaches: Due to the increased resources needed to render frames in VR performance can be more affected, and for an immersive experience more fine-tuning could be required.
- AI-Assisted Style Refinement, to both improve the overall artistic feel of certain scenes and maybe allow for further visibility improvements.

4.3. Final Remarks

Modern game graphics inhabit a tricky intersection of art, physics, and occasionally the bizarre wizardry known as shader math. Our work shows that by channeling clever matrix algebra, local gradient operators, and style objectives, developers can conjure a genuinely inclusive and artistically unique experience. Our solution allows for more players to enjoy a game, the visuals stay fresh across frames, and performance remains stable enough that players can keep clicking heads (or swords, or spells) to their heart's content.

In the end, accessibility and visual innovation need not collide. Instead, they can complement each other in a unified pipeline that respects both the user's functional needs and the designer's aesthetic ambitions. By taking advantage of these relatively low-cost GPU enhancements, studios of all sizes, AAA behemoths, and indie devs alike can bring their unique visions to a broader audience and, in doing so, elevate the entire medium of interactive digital art.

Acknowledgment

The authors acknowledge the use of ChatGPT to help with paraphrasing some of the text to better match the English language, as well as organize the References and Bibliography.

References

[1] Gustavo M. MACHADO, Manuel M. OLIVEIRA, Leandro A.F. FERNANDES - *A physiologically-based model for simulation of color vision deficiency* - IEEE Transactions on Visualization and Computer Graphics, volume 15 no. 6. ISSN 1077-2626. Pages 1291–1298. October 2009.

[2] Holger WINNEMÖLLER, Sven C. OLSEN, Bruce GOOCH - *Real-time video abstraction* - ACM Transactions on Graphics, volume 25 no. 3. ISSN 0730-0301. Pages 1221–1226. July 2006.

[3] James S. WOLFFSOHN, Ditipriya MUKHOPADHYAY, Martin RUBINSTEIN - *Image enhancement of real-time television to benefit the visually impaired* - American Journal of Ophthalmology, volume 144 no. 3. ISSN 0002-9394. Pages 436–440. September 2007.

[4] Elmar EISEMANN, Xavier DÉCORET - *Visibility sampling on GPU and applications* - Computer Graphics Forum, volume 26 no. 3, ISSN 1467-8659. Pages 535–544. September 2007.

[5] Françoise VIÉNOT, Hans BRETTEL, John D. MOLLON - *Digital video colourmaps for checking the legibility of displays by dichromats* - Color Research & Application, volume 24 no. 4. ISSN 0361-2317. Pages 243–252. June 1999.

[6] Emanuele AGRIMI, Chiara BATTAGLINI, Davide BOTTARI, Giorgio GNECCO, Barbara LEPORINI - *Game accessibility for visually impaired people: a review* - Soft Computing, volume 28 no. 17. ISSN 1432-7643. Pages 10475–10489. July 2024.

[7] Manuel RUDER, Alexey DOSOVITSKIY, Thomas BROX - *Artistic style transfer for videos* - In Pattern Recognition: 38th German Conference, GCPR 2016, Hannover, Germany, September 12–15, 2016, Proceedings. ISBN 978-3-319-45886-1. Pages 26–36. August 2016.

[8] Dongdong CHEN, Jing LIAO, Lu YUAN, Nenghai YU, Gang HUA - *Coherent online video style transfer* - In Proceedings of the IEEE International Conference on Computer Vision. ISBN 9781538610336. Pages 1105–1114. 2017.

[9] Leon A. GATYS, Alexander S. ECKER, Matthias BETHGE - *Image style transfer using convolutional neural networks* - In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. ISBN 9781467388528. Pages 2414–2423. 2016.

[10] Tomas AKENINE-MÖLLER, Eric HAINES, Naty HOFFMAN - *Real-time rendering* – Pages 267-292, 651-680. ISBN 9781315365459. Published by AK Peters/CRC Press, New York–London–Sydney. 2019.

[11] Elio SASSO, Daniele LOIACONO, Pier Luca LANZI - *A Tool for the Procedural Generation of Shaders Using Interactive Evolutionary Algorithms* - 2024 IEEE Gaming, Entertainment, and Media Conference (GEM). ISSN: 2766-6530. Pages 1–4. June 2024.

[12] Wenbo BAO, Wei-Sheng LAI, Chao MA, Xiaoyun ZHANG, Zhiyong GAO, Ming-Hsuan YANG - *Depth-aware video frame interpolation* - In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. ISBN 9781728132945. Pages 3703–3712. 2019.

[13] Biruk Mengistu - *Deep-Learning Realtime Upsampling Techniques in Video Games* - Scholarly Horizons: University of Minnesota, Morris Undergraduate Journal, volume 10 no. 2. ISSN 2573-0037. Article 4. June 2023.

[14] Dmytro ZUBOV, Andrey KUPIN, Nurlan SHAIDULLAEV, Rita ISMAILOVA - *Indoor Spatial Cognition for the Hearing/Visually Impaired: Google ARCore Augmented Interaction Using WiFi Map* - BRAIN. Broad Research in Artificial Intelligence and Neuroscience, volume 15 no. 4. ISSN 2067-3957. Pages 27–37. 2024.

[15] I. C. Stanica, F. Moldoveanu, M. I. Dascalu, A. Moldoveanu, G. P. Portelli, and C. N. Bodea - *Neurorehabilitation system using virtual reality and MYO armband for patients and medical personnel training* - Revue Roumaine des Sciences Techniques, Série Électrotechnique et Énergétique, volume 65 no. 1-2. ISSN: 0035-4066. Pages 139-144. January 2020.

[16] I. C. Stanica, A. Moldoveanu, I. Dascalu, F. Moldoveanu, M. Radoi, and I. V. Nemoianu - *Emergent technologies to enrich reading outcomes through augmented reality* - Revue Roumaine des Sciences Techniques, Série Électrotechnique et Énergétique, volume 64 no. 1. ISSN: 0035-4066. Pages 95–100. January 2019.

[17] A. Moldoveanu, O. Balan, M. I. Dascalu, I. Stanica, C. N. Bodea, R. Unntorson, and F. Moldoveanu - *Sound of vision 3D virtual training environments—a gamification approach for visual to audio-haptic sensory substitution* - Revue Roumaine des Sciences Techniques Serie Électrotechnique et Énergétique, volume 63 no. 1. ISSN: 0035-4066. Pages 112–117. January 2018.

[18] Shanbname Sadeghi ESFAHLANI, Tommy THOMPSON, Ali Davod PARSA, Ian BROWN, and Silvia CIRSTEA - *ReHabgame: A non-immersive virtual reality rehabilitation system with applications in neuroscience* – Heliyon, volume 4 no. 2. ISSN 2405-8440. February 2018.

[19] Amandine AFONSO-JACO and Brian F.G. KATZ - *Spatial knowledge via auditory information for blind individuals: spatial cognition studies and the use of audio-VR* - Sensors, volume 22 no. 13. ISSN: 1424-8220. Pages 4794. June 2022.

[20] http://and.intercon.ru/releases/talks/dlaagdc2011 - Dmitry ANDREEV, A Directionally Localized Anti-Aliasing Approach Accessed: 19-03-2025.

[21] https://reshade.me - CROSIRE, ReShade Program 19-03-2025.

[22] https://docs.unrealengine.com/5.0/en-US/post-process-materials-in-unreal-engine - EPIC GAMES, Post Process Materials in Unreal Engine 5 19-03-2025.

[23] https://docs.unrealengine.com/5.0/en-US/post-process-volumes-in-unreal-engine-5 - EPIC GAMES, Post Process Volumes Overview 19-03-2025.

[24] Jan Eric KYPRIANIDIS, Amir SEMMO, Henry KANG, Jürgen DÖLLNER - *Anisotropic Kuwahara Filtering with Polynomial Weighting Functions* – In Theory and Practice of Computer Graphics TPCG10. ISBN 978-3-905673-75-3. Pages 25–30. September 2010.

Bibliography

AFONSO-JACO Amandine, KATZ Brian F.G. – Spatial knowledge via auditory information for blind individuals: spatial cognition studies and the use of audio-VR – Sensors, volume 22 no. 13. ISSN: 1424-8220. Pages 4794. June 2022.

AGRIMI Emanuele, BATTAGLINI Chiara, BOTTARI Davide, GNECCO Giorgio, LEPORINI Barbara – Game accessibility for visually impaired people: a review – Soft Computing, volume 28 no. 17. ISSN 1432-7643. Pages 10475–10489. July 2024.

AKENINE-MÖLLER Tomas, HAINES Eric, HOFFMAN Naty – Real-time rendering – ISBN 9781315365459. AK Peters/CRC Press. Pages 267–292, 651–680. August 2019.

BAO Wenbo, LAI Wei-Sheng, MA Chao, ZHANG Xiaoyun, GAO Zhiyong, YANG Ming-Hsuan – Depth-aware video frame interpolation – Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. ISBN 9781728132945. Pages 3703–3712. 2019.

CHEN Dongdong, LIAO Jing, YUAN Lu, YU Nenghai, HUA Gang – Coherent online video style transfer – Proceedings of the IEEE International Conference on Computer Vision. ISBN 9781538610336. Pages 1105–1114. 2017.

EISEMANN Elmar, DÉCORET Xavier – Visibility sampling on GPU and applications – Computer Graphics Forum, volume 26 no. 3. ISSN 1467-8659. Pages 535–544. September 2007.

ESFAHLANI Shanbname Sadeghi, THOMPSON Tommy, PARSA Ali Davod, BROWN Ian, CIRSTEA Silvia – ReHabgame: A non-immersive virtual reality rehabilitation system with applications in neuroscience – Heliyon, volume 4 no. 2. ISSN 2405-8440. February 2018.

FAN Hongbin, ZHANG Hao – Saliency-based image correction for colorblind patients – Visual Computing for Industry, Biomedicine, and Art. ISSN 2096-0500. December 2020.

GATYS Leon A., ECKER Alexander S., BETHGE Matthias – Image style transfer using convolutional neural networks – Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. ISBN 9781467388528. Pages 2414–2423. 2016.

GONÇALVES Daniel, PIÇARRA Mafalda, PAIS Pedro, GUERREIRO João, RODRIGUES André – My Zelda Cane: Strategies Used by Blind Players to Play Visual-Centric Digital Games – arXiv preprint arXiv:2301.08031. 2023.

JAMIL Abdullah, DENES Gabriella – Investigating Color-Blind User Interface Accessibility via Simulated Interfaces – Computers, volume 13 no. 2. ISSN 2073-431X. Article 53. 2024.

KYPRIANIDIS Jan Eric, SEMMO Amir, KANG Henry, DÖLLNER Jürgen – Anisotropic Kuwahara Filtering with Polynomial Weighting Functions – In Theory and Practice of Computer Graphics (TPCG10). ISBN 978-3-905673-75-3. Pages 25–30. September 2010.

MACHADO Gustavo M., OLIVEIRA Manuel M., FERNANDES Leandro A.F. – A physiologically-based model for simulation of color vision deficiency – IEEE Transactions on Visualization and Computer Graphics, volume 15 no. 6. ISSN 1077-2626. Pages 1291–1298. October 2009.

MENGISTU Biruk – Deep-Learning Realtime Upsampling Techniques in Video Games – Scholarly Horizons: University of Minnesota, Morris Undergraduate Journal, volume 10 no. 2. ISSN 2573-0037. Article 4. June 2023.

MOLDOVEANU Adrian, BALAN Octavian, DASCALU Mihai I., STANICA Ionut C., BODEA Cristian N., UNNTORSON R., MOLDOVEANU Florin – Sound of vision 3D virtual training environments – Revue Roumaine des Sciences Techniques Serie Électrotechnique et Énergétique, volume 63 no. 1. ISSN: 0035-4066. Pages 112–117. January 2018.

NAVSTICK – Making Video Games Blind-Accessible via the Ability to Look Around – arXiv preprint arXiv:2109.01202. 2021.

RUDER Manuel, DOSOVITSKIY Alexey, BROX Thomas – Artistic style transfer for videos – Pattern Recognition: 38th German Conference, GCPR 2016, Proceedings. ISBN 978-3-319-45886-1. Pages 26–36. August 2016.

SASSO Elio, LOIACONO Daniele, LANZI Pier Luca – A Tool for the Procedural Generation of Shaders Using Interactive Evolutionary Algorithms – 2024 IEEE Gaming, Entertainment, and Media Conference (GEM). ISSN: 2766-6530. Pages 1–4. June 2024.

SEO Seongho, PARK Jinwoo – Color Universal Design Neural Network for the Color Vision Deficiencies – arXiv preprint arXiv:2502.08671. 2025.

STANICA I. C., DASCALU M. I., MOLDOVEANU A., MOLDOVEANU F., RADOI M., NEMOIANU I. V. – Emergent technologies to enrich reading outcomes through augmented reality – Revue Roumaine des Sciences Techniques, Série Électrotechnique et Énergétique, volume 64 no. 1. ISSN 0035-4066. Pages 95–100. January 2019.

STANICA I. C., MOLDOVEANU F., DASCALU M. I., MOLDOVEANU A., PORTELLI G. P., BODEA C. N. – Neurorehabilitation system using virtual reality and MYO armband for patients and medical personnel training – Revue Roumaine des Sciences Techniques, Série Électrotechnique et Énergétique, volume 65 no. 1-2. ISSN 0035-4066. Pages 139-144. January 2020.

VIÉNOT Françoise, BRETTEL Hans, MOLLON John D. – Digital video colourmaps for checking the legibility of displays by dichromats – Color Research & Application, volume 24 no. 4. ISSN 0361-2317. Pages 243–252. June 1999.

WINNEMÖLLER Holger, OLSEN Sven C., GOOCH Bruce – Real-time video abstraction – ACM Transactions on Graphics, volume 25 no. 3. ISSN 0730-0301. Pages 1221–1226. July 2006.

WOLFFSOHN James S., MUKHOPADHYAY Ditipriya, RUBINSTEIN Martin – Image enhancement of real-time television to benefit the visually impaired – American Journal of Ophthalmology, volume 144 no. 3. ISSN 0002-9394. Pages 436–440. September 2007.

ZHOU Zheng, LIN Yuheng – Improving Discrimination in Color Vision Deficiency by Image Re-Coloring – Sensors, volume 19 no. 10. ISSN 1424-8220. Article 2250. May 2019.

http://and.intercon.ru/releases/talks/dlaagdc2011 – Dmitry ANDREEV, A Directionally Localized Anti-Aliasing Approach. 19-03-2025.

https://docs.unrealengine.com/5.0/en-US/post-process-materials-in-unreal-engine – EPIC GAMES, Post Process Materials in Unreal Engine 5. 19-03-2025.

https://docs.unrealengine.com/5.0/en-US/post-process-volumes-in-unreal-engine-5 – EPIC GAMES, Post Process Volumes Overview. 19-03-2025.

https://reshade.me – CROSIRE, ReShade Program. 19-03-2025.

CLUSTER ANALYSIS ON THE USE OF GENERATIVE AI TOOLS BY INDIVIDUALS IN EUROPEAN UNION CONTRIES

Marian ZAHARIA[1]
Camelia-Monica GHEORGHE[2]
Cristiana-Ștefania ANTONOVICI[3]

Abstract
In recent times, artificial intelligence (AI) has gone beyond the stage of a tool, becoming for a fairly wide audience a consultant, a personal assistant with expertise in a variety of fields, from private to professional purposes, as well as, last but not least, in formal education. This attribute is underlined by the significant shares of the various categories of the population that use generative AI tools (GAIT). Considering this aspect, the paper presents the results of the analyses undertaken by the authors on the similarities and disparities between twenty-four EU member states regarding the shares of the use of GAIT by individuals according to the levels of education and the age groups they belong to, for private purposes (PP), professional purposes (WP) and educational purposes (FE). The results obtained highlight significant differences both between the different categories of individuals and between the states they belong to.

Keywords: Artificial Intelligence, AI tools, cluster analysis, hierarchic cluster methodology, private purpose, professional purpose, formal education

JEL Classification: C12, C18, C38, D19, I20

1. Introduction

As artificial intelligence technologies evolve, more and more individuals and organizations are becoming users of AI [1] for a wide range of purposes, from private purposes to educational purposes, as well as in professional activities.

In professional activity, the use of generative AI tools (GAIT) has the role of automating, integrating and amplifying human creativity in work [2,3], being a factor in increasing productivity [4]. In these conditions, although managerial factors are interested in adopting AI in activities to optimize and increase their economic efficiency, it is necessary that the implementation of GAIT be based on ethics and produce people-centered results [5].

[1] PhD Professor, Oil and Gas University Ploiesti, Romania, marianzaharia53@gmail.com
[2] PhD Lecturer, Romanian-American University, Romania, camelia.gheorghe@rau.ro
[3] PhD Assistant, Romanian-American University, Romania, stefania.antonovici@rau.ro

Also, in the development of the educational level of individuals, in general, and especially in formal education, generative AI tools play an increasingly important role, with students showing a positive attitude towards them [6]. Their integration into course assignments improves student involvement, promoting dynamic learning environments, which can lead both to reducing the time needed to solve assignments, and to an increase in efficiency and creativity in solving them [7]. However, on the other hand, it can also generate risks related to the quality and authenticity of the works. In these conditions, the transformations brought by the use of AI require the reform of traditional educational systems [8], its responsible integration into educational processes [9], taking into account the ethical challenges associated with the large-scale adoption of AI in research and academia [130].

In addition to the advantages, the rapid and large-scale development of generative AI tools also brings a series of risks [11] regarding training and data validation issues, information leaks, intellectual property, privacy violations, misinformation, and amplification of prejudices, which imposes the need for innovative and inclusive approaches to ensure the development of GAIT in line with social values.

Individuals' willingness to use generative AI tools (GAIT), the intensity and frequency of their use, depend on the context [12], the diversity of socio-economic factors, certain attitudes and subjective norms [13], with a more intense use observed among individuals with higher education, as well as among younger people, especially students [14].

In this context, the objective of the paper was to analyses the similarities and disparities between the member states of the European Union regarding the shares of use of generative AI tools for private purposes, professional (work) purposes and formal education depending on the level of education and age groups of individuals, in the year 2025.

2. Research methodology

Taking into account the main objective of the paper, two cluster analyses were carried out. The first of these aimed to identify similarities between EU member states regarding the shares of use of GAIT for private purposes (PP), work purpose (WP) and formal education purposes (FE) according to the educational attainment levels of the population aged 16 to 74 [15]: less than primary, primary and lower secondary (LPLS) education (levels 0-2), upper secondary and post-secondary non-tertiary (USNT) education (levels 3-4) and tertiary (TE) education (levels 5-8). The indicators included in this first analysis, regarding the relationship between educational level (EL) and GAIT used, are presented in Table 1

The second analysis is a refinement of the first analysis by including, along with the three levels of education (LPLS, USNT and TE), the segmentation of the population aged 16 to 74 into three age groups: 16 – 24 years, 25 – 54 years and 55 – 74 years.

Ind.	Signification	Units
IUPP	Individuals which use AI tools for private purposes	%
IUWP	Individuals which use AI tools for professional (work) purposes	%
IUFE	Individuals which use AI tools for formal education	%
PLPLSE	Population with LPLS education	%
PUSNTE	Population with USNT education	%
PTE	Population with TE education	%

Table 1 Indicators included in analysis of the relationship EL-AI tools

The main data sources were: Population in private households by educational attainment level [16] and Individuals - use of generative AI tools [17]. However, given that the data series for individuals aged 16-24 with tertiary education which uses GAIT, as well as for individuals aged 25-54 and 55-74 with LPLS education level which uses generative AI tools, show many discontinuities, these were not included in the analyses. Also, given that the data series for Hungary, Croatia and Malta show either discontinuities or low reliability, only the other twenty-four Member States of the European Union were included in the analyses. The indicators used are presented in Table 2.

For highlighting the similarities and disparities between the twenty-four states included in the analyses we used the hierarchical clustering analysis, founded by Johnson S.C. in 1967 [18] and D'Andrade in 1978 [19]. In applying the hierarchical clustering methodology, we started from matrices of the form $Y = \left\| y_{ij} \right\|_{\overline{i=1,n}, \overline{j=1,r}}$, where $n = 24$ and represents the number of states included in the analysis, and r is the number of indicators according to the values of which the clusters are generated. In the first analysis $r = 7$, and in the second $r = 24$. Starting from these, squared Euclidian distance was used to generate the proximity matrix [20], and Ward's method was used to generate the clusters [21].

To test the statistical significance of the membership of the variables in the clusters, as well as their means, the ANOVA method (variance analysis) was used, the applicability of which is conditional on verifying the homoscedasticity of the data series, and the Welch test (Robust Tests of Equality of Means).

To verify the homoscedasticity of the data series, the Levene test was used, with the null hypothesis (H_{01}):

- H_{01}: variance does not differ significantly (homoscedasticity), the condition of acceptance being: $L<F_{(\alpha,r-1,n-r)}$ or $Sig>\alpha$ where L is Levene statistic.

Ind.	Signification	Units
L16PP	Individuals aged 16-24 with PLSE which uses AI tools for PP	%
L16WP	Individuals aged 16-24 with PLSE which uses AI tools for WP	%
L16FE	Individuals aged 16-24 with PLSE which uses AI tools for FE	%
M16PP	Individuals aged 16-24 with USNTE which uses AI tools for PP	%
M16WP	Individuals aged 16-24 with USNTE which uses AI tools for WP	%
M16FE	Individuals aged 16-24 with USNTE which uses AI tools for FD	%
M25PP	Individuals aged 25-54 with USNTE which uses AI tools for PP	%
M25WP	Individuals aged 25-54 with USNTE which uses AI tools for WP	%
M25FE	Individuals aged 25-54 with USNTE which uses AI tools for FE	%
H25PP	Individuals aged 25-54 with TE which uses AI tools for PP	%
H25WP	Individuals aged 25-54 with TE which uses AI tools for WP	%
H25FE	Individuals aged 25-54 with TE which uses AI tools for FE	%
M55PP	Individuals aged 55-74 with USNTE which uses AI tools for PP	%
M55WP	Individuals aged 55-74 with USNTE which uses AI tools for WP	%
H55PP	Individuals aged 55-74 with TE which uses AI tools for PP	%
H55WP	Individuals aged 55-74 with TE which uses AI tools for WP	%

Table 2 Indicators included in analysis of the relationship EL-AG-AI tools,

If hypothesis H_{01} is accepted, to test the significance of the membership of the variables to the clusters, the ANOVA methodology (F test) can be used, with the null hypothesis H02:

- H_{02}: the membership of the variable to the clusters is not significant (the average values of the variable recorded at the cluster level do not differ significantly) the condition for accepting the hypothesis being $F_{stat} < F_{\alpha,r-1,n-r}$ or Sig $> \alpha$

If the hypothesis H_{01} is rejected, instead of the ANOVA methodology, Welch robust tests of equality of means can be used, the null hypothesis H_{03} being:

- H_{03}: the mean values of the variable recorded at the cluster level do not differ significantly, the acceptance condition being $W < F_{\alpha,r-1,\ df}$ or Sig>α, where W is Welch statistic.

For testing the statistical hypotheses, the significance level used was 95% (α = 0.05).

3. Similarities and disparities regarding the relationship between the population's education level and AI tools used

The analysis of similarities and disparities between the twenty-four EU member states included in the analysis was carried out according to six indicators (Table 1), three of which refer to the purpose of using generative AI tools (IUPP, IUWP and IUFE) and the other three to the level of education of users (PLPLSE, PUSNTE and PTE).

3.1. Cluster generation and validation

Following the analyses and tests carried out, depending on the values of variables recorded in 2025 at the level of the each state, a grouping into seven clusters resulted, including between two and six states. The dendrogram of cluster generation is illustrated in figure 1.

Clusters	Structure of clusters
A	Belgium, Greece, France, Netherlands, Austria, Finland
B	Bulgaria, Czechia, Poland, Slovakia
C	Denmark, Estonia, Sweden
D	Germany, Latvia, Lithuania, Slovenia
E	Ireland, Cyprus, Luxembourg
F	Spain, Portugal
G	Italy, Romania

Table 3 The structure of clusters generated based on EL-AI tools used relationships

Among the seven clusters (Table 3) the most numerous is cluster A which includes six states. Clusters B and D include four states, clusters C and E include three states, and clusters E and F include two states each.

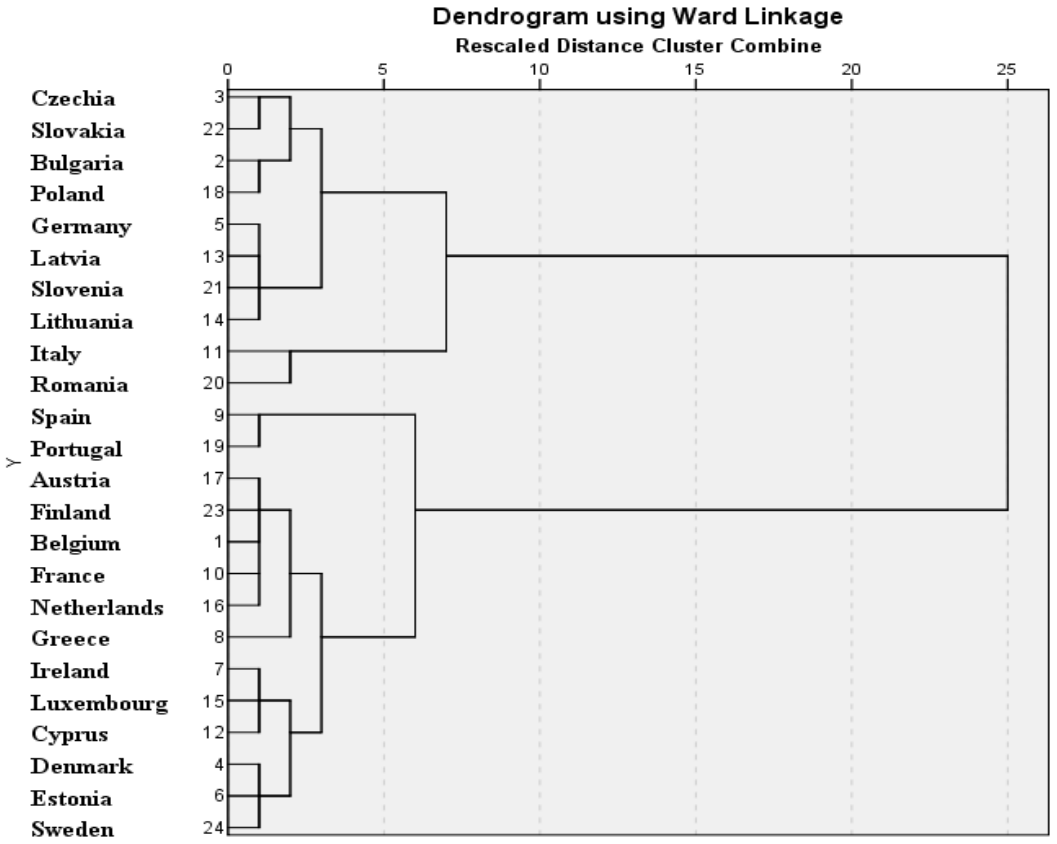


Figure 1. Dendogram of cluster generation based on EL-GAIT used relationships

The Levene test (Test of Homogeneity of Variance) was used to test the homogeneity of variances of the data series. The results obtained (Table 4a) highlight the fact that, for the variables PLPLSE and PUSNTE, for which Sig<0.050, the null hypothesis H_{01} is rejected and, consequently, the ANOVA methodology cannot be used to test the statistical significance of the variables belonging to clusters. Under these conditions, the Welch test (Robust Test of Equality of Means) was used to verify the statistical significance of the mean values of the variables, recorded at the cluster level. Considering that in this case all

the values Sig<0.050 (Table 4b), the null hypothesis H_{03} is rejected. All the mean values of the variables recorded at the cluster level are statistically significant.

a. Test of Homogeneity of Variances				
	Levene Statistic	df1 r-1	df2 n-r	Sig.
IUPP	1,151	6	17	,376
IUWP	1,040	6	17	,434
IUFE	1,113	6	17	,395
PLPLSE	4,086	6	17	,010
PUSNTE	9,278	6	17	,000
PTE	1,500	6	17	,237

b. Robust Test of Equality of Means				
	Welch Statistic	df1 r-1	df2	Sig.
IUPP	26,767	6	5,937	,000
IUWP	18,297	6	5,620	,002
IUFE	10,292	6	5,286	,009
PLPLSE	13,157	6	5,112	,006
PUSNTE	17,338	6	5,099	,003
PTE	28,144	6	5,311	,001

Table 4 Results of Levene (A) and Welch (B) statistical tests

3.2. Similarities and disparities between EU member countries regarding the relationships between users' education level and GAIT used by individuals

The results of the cluster analysis on the relationships between the level of education of users (EL) and GAIT used by individuals highlight both similarities and disparities between the twenty-four EU member states included in the analysis, leading to their grouping into seven clusters.

Variables	Clusters						
	A	B	C	D	E	F	G
IUPP	32,02	23,28	35,32	29,33	36,63	31,71	13,83
IUWP	21,37	10,33	24,43	16,14	23,32	18,94	6,62
IUFE	11,88	6,80	18,09	8,00	13,06	15,36	4,87
PLPLSE	22,92	13,98	20,53	16,33	21,10	42,45	31,75
PUSNTE	42,42	59,50	41,37	50,68	33,67	26,75	51,55

PTE	34,62	26,53	38,03	33,03	45,23	30,80	16,75

Table 5 Average values (%) of variables at cluster level

In terms of the average values recorded at the cluster level (Table 5), the best performers are clusters C and E with high average values of the shares of individuals who used GAIT in 2025 as well as of the population with tertiary education.

Cluster C (Denmark, Estonia, Sweden) ranks first in the use of AI tools by individuals for professional purposes (IUWP=24.43%) and formal educational purposes (IUFE=18.09%) and second, after cluster E, in the use of GAIT for private purposes (IUPP=35.32%), as well as the share of the population with tertiary education (PTE=38.03%). On the other hand, in cluster C there are relatively low values of the share of the population with low education (PLPLSE=20.53%).

Cluster E (Ireland, Cyprus, Luxembourg) is characterized by the highest share of individuals using GAITs for private purposes (IUPP=36.63%), as well as the highest share of the population with tertiary education (PTE=45.23%). It also ranks second in terms of the share of individuals using GAITs for professional purposes (IUWP=23.32%), as well as some of the lowest shares of the population with medium levels of education (PUSNTE=33.67%).

At the opposite end, with the lowest shares of individuals using GAITs are clusters B and G. These are also the clusters where the highest values of the share of the population with USNT education level are recorded, as well as the lowest values of the share of the population with tertiary education level (TE). The disparities compared to clusters C and E are evident (Figure 2).

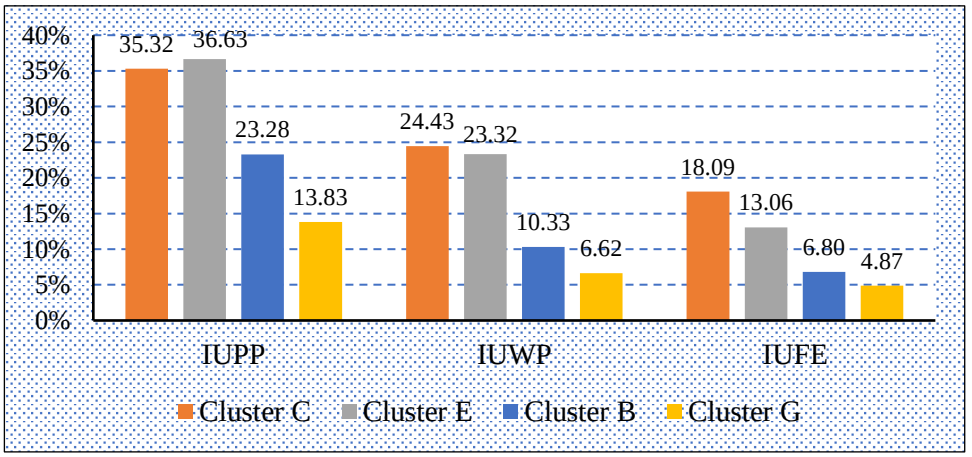


Figure 2 Disparities between clusters C, E, B and G regarding the shares of individuals using AI tools for private (IUPP), professional (IUWP) and educational purposes (IUFE)

Thus, in cluster G (Italy and Romania), at the level of the year 2025, the lowest values of IUPP (13.83%), IUWP (6.62%) and IUFE (4.86%) were recorded, values 2.64 times lower than the IUPP value recorded in cluster E and 3.72 times lower than the IUFE value recorded in cluster C. Also, the lowest value of the share of the population with tertiary education (PTE=16.75%) is recorded here, 2.70 times lower than in cluster E.

Although cluster B (Bulgaria, Czechia, Poland and Slovakia) is characterized by values close to cluster G, values that place it in the penultimate place in IUPP (23.28%), IUWP (10.33%) and IUFE (6.80%) and (PTE=26.53%), these clusters differ fundamentally in terms of the share of the population with LPLS education level. Thus, while in cluster B the average value of PLPLSE was 13.98%, in cluster G it was 31.75%, 2.27 times higher.

As for the other three clusters, they are in the median area in terms of the share of individuals using GAIT, but they show significant differences in terms of population shares according to education levels. While, by the values recorded in 2025, cluster A (Belgium, Greece, France, Netherlands, Austria and Finland) ranks third in terms of IUPP (32.02%), IUWP (21.37%), PLPLSE (22.92%) and PTE (34.62%) and 4th in terms of IUFE (11.88%) and PUSNTE (42.42%), cluster D (Germany, Latvia, Lithuania and Slovenia) ranks fifth in the shares of individuals using GAIT, regardless of the purpose of their use, with significantly higher shares (by 8.26 percentage points) than in cluster A regarding PUSNTE (50.68%) and significantly lower (by 6.59 percentage points) regarding PLPLSE (16.33%).

Cluster F (Spain and Portugal), although in terms of IUPP and IUPW it is between clusters A and D, records the second value of IUFE (15.36%), with only 2.73 percentage points less than the highest value (18.09%) recorded in cluster C and with 3.48 and 7.36 percentage points more than in clusters A and D. In terms of education levels, cluster F recorded the highest value of PLPLSE (42.45%) and the lowest value of PUSNTE (26.75%).

Analysing the characteristics of the clusters resulting from the relationships between the level of education of the population and the use of GAIT, significant differences emerged between the shares of the purposes for which individuals used these tools, as well as between the education levels of the users. It turned out that the level of education influences the shares of GAIT use, between them being a direct positive relationship. On the other hand, in terms of the purpose of using GAIT, in all clusters, private purposes were in first place, followed by professional purposes and only in third place by educational purposes, the shares being influenced by the educational level of the population.

4. Similarities and disparities regarding the relationship between user age groups, educational level and purposes of GAIT use

The second cluster analysis aimed to analyze the relationship between the age groups of users and the purposes for which they used GAIT in 2025. Three age groups were included in the analysis: 16-24 years, 25-54 years and 55-74 years. Regarding the purposes for which individuals used GAIT, as well as the levels of education, these were those used in the previous analysis, private purpose (PP), professional purpose (WP), educational purpose (EP), less than primary, primary and lower secondary (LPLS) education, upper secondary and post-secondary non-tertiary (USNT) education and tertiary education (TE).

4.1. Cluster generation and validation

In this second cluster analysis, taking into account the values of the sixteen variables, as well as the analyses and tests performed, a grouping into six clusters resulted, including between two and six states, with one exception (Sweden). The dendrogram of cluster generation taking into account education levels (EL), age groups (AG) and GAIT used is illustrated in figure 3.

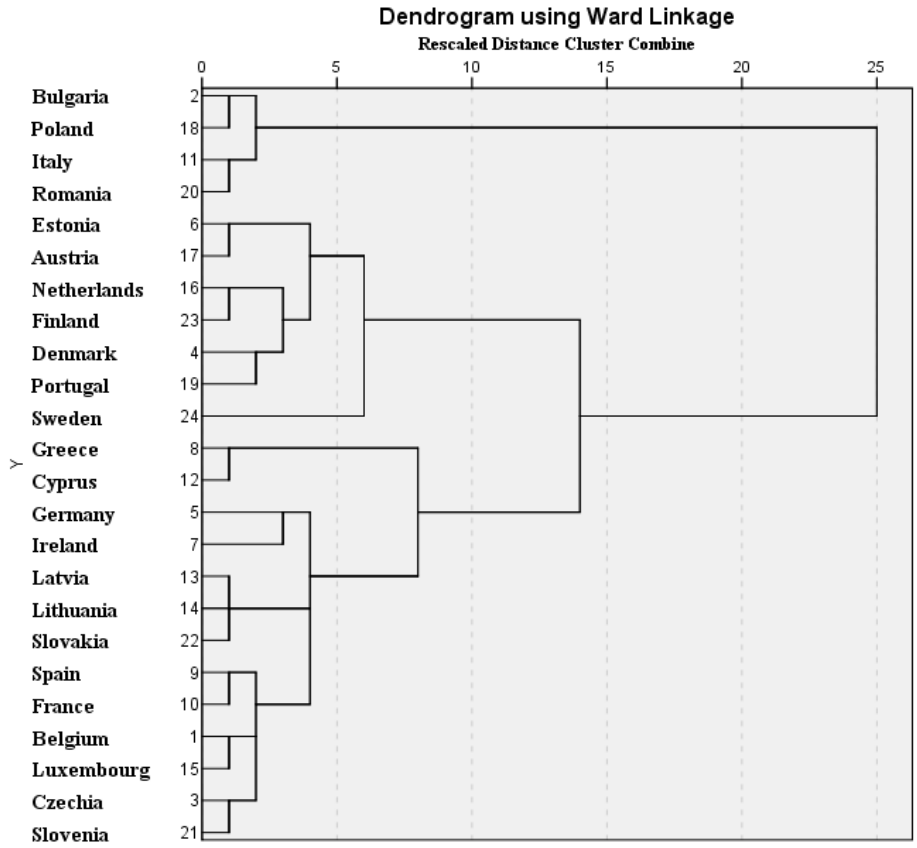


Figure 3. Dendogram of cluster generation based on EL-AG-GAIT relationships

Among the six clusters (Table 6), clusters A and C each include six states, cluster B includes four states, cluster F includes three states, and clusters D and E each include two states.

Clusters	Structure of clusters
A	Belgium, Czechia, Spain, France, Luxembourg, Slovenia
B	Bulgaria, Italia, Poland, Romania
C	Denmark, Estonia, Netherlands, Austria, Portugal, Finland
D	Germany, Ireland
E	Greece Cyprus
F	Latvia, Lithuania, Slovakia

Table 6 The structure of clusters generated based on EL-AG-AI tools relationships

By taking into account the age groups of users, several changes occurred in the structure of the clusters. Thus, in cluster A only Belgium and France remained, joined by Czechia (from cluster B), Slovenia (from cluster D), Luxembourg (from cluster E) and Spain (from cluster F), while the Netherlands, Austria and Finland, together with Portugal (from cluster F) with Denmark and Estonia now form cluster C. In cluster B, of the four states, Bulgaria and Poland remained, joined by Italy and Romania (from cluster G). In cluster D, of the four states, only Germany remained, joined by Ireland (from cluster E). In cluster E, of the three states, only Cyprus remained, joined by Greece (from cluster A). Latvia and Lithuania (from cluster E) together with Slovakia (from cluster B) now form cluster F. Finally, in this new structuring, Sweden is not included in any cluster, constituting an exception.

Also, in this second analysis, the Levene test (Test of Homogeneity of Variance) was used to test the homogeneity of variances of the data series, the results being presented in Table 7. Taking into account the fact that all LS (Levene Statistic) values are lower than $F(0,05;5;17)=2.810$ ($Sig>\alpha=0,05$), it results that the null hypothesis H01 is accepted and, consequently, the ANOVA methodology can be used to test the statistical significance regarding the membership of the variables in clusters.

Considering that, in this case, there are 6 clusters ($r=6$) and 18 variables ($n=18$), the ANOVA methodology was applied, namely the F test, for $\alpha=0.05$ and degrees of freedom $df1=5$ and $df2=17$, whose critical value is $F(0.05;5;17)=2.809$. The results obtained (Table 8) highlight

the fact that all Sig values <0.050, which leads to the rejection of the null hypothesis H02. All mean values of the variables recorded at the cluster level are statistically significant

Variables	LS	df1 (r-1)	df2 (n-r)	Sig.	Variables	LS	df1 (r-1)	df2 (n-r)	Sig.
L16PP	,970	5	17	,464	M25FE	,718	5	17	,619
L16WP	2,544	5	17	,068	H25PP	2,683	5	17	,058
L16FE	2,177	5	17	,105	H25WP	1,526	5	17	,234
M16PP	2,411	5	17	,080	H25FE	2,202	5	17	,102
M16WP	2,028	5	17	,126	M55PP	,824	5	17	,550
M16FE	2,727	5	17	,055	M55WP	2,278	5	17	,093
M25PP	2,495	5	17	,072	H55PP	1,351	5	17	,291
M25WP	1,336	5	17	,296	H55WP	1,841	5	17	,158

Table 7 Results of Levene tests

Variables	F	df1 (r-1)	df2 (n-r)	Sig.	Variables	F	df1 (r-1)	df2 (n-r)	Sig.
L16PP	,970	5	17	,464	M25FE	,718	5	17	,619
L16WP	2,544	5	17	,068	H25PP	2,683	5	17	,058
L16FE	2,177	5	17	,105	H25WP	1,526	5	17	,234
M16PP	2,411	5	17	,080	H25FE	2,202	5	17	,102
M16WP	2,028	5	17	,126	M55PP	,824	5	17	,550
M16FE	2,727	5	17	,055	M55WP	2,278	5	17	,093
M25PP	2,495	5	17	,072	H55PP	1,351	5	17	,291

M25WP	1,336	5	17	,296	H55WP	1,841	5	17	,158

Table 8 Results of ANOVA test

4.2. Similarities and disparities between EU member countries regarding the relationships between age groups, education level and GAIT used by individuals

The results of the cluster analysis on the relationships between education level (EL), age group (AG) and GAIT used by individuals (Table 9) highlight a much greater number of similarities and disparities between the countries included in the analysis.

	Clusters					
	A	B	C	D	D	F
L16PP	50,73	28,46	50,52	34,11	71,63	53,66
L16WP	5,62	2,16	12,70	13,28	7,30	5,84
L16FE	57,67	33,20	52,07	30,35	47,28	53,81
M16PP	53,09	34,55	54,84	46,17	74,90	54,16
M16WP	17,46	4,92	26,48	23,35	8,41	16,96
M16FE	52,58	26,06	50,41	40,94	60,11	40,35
M25PP	28,66	15,76	35,02	39,00	29,58	22,23
M25WP	14,09	6,37	23,64	13,37	8,49	8,39
M25FE	4,68	1,50	11,11	4,78	3,96	3,12
H25PP	49,80	33,24	49,88	41,97	68,04	50,71
H25WP	42,55	22,47	49,90	36,62	44,54	36,86
H25FE	9,60	4,32	16,01	8,66	14,30	9,50
M55PP	9,56	3,72	11,03	8,74	13,00	3,57
M55WP	3,22	1,44	6,23	3,08	4,20	0,80

H55PP	25,30	14,20	24,17	17,76	38,63	16,92
H55WP	15,98	9,98	21,63	12,76	20,68	10,63

Table 9 Average values (%) of variables at cluster level generated based on EL-AG-GAIT relationships

From the point of view of the use of GAIT by individuals for private purposes (PP), if in the first analysis the average shares ranged between a maximum of 36.63% and a minimum of 13.83% (Table 5), by taking into account the age groups (Table 9), the average values range between a maximum of 74.90%, a value recorded in cluster E (Greece and Cyprus), for individuals in the age group 16-24 years and with USNT education level (M16PP) and a minimum of 3.57%, a value recorded in cluster F (Latvia, Lithuania and Slovakia) for individuals in the age group 55-74 years and USNT education level (M55PP).

A relevant image of the differences between the first three clusters regarding the shares of GAIT use by individuals is illustrated in figure 4. Thus, in five of the six age groups and education levels the highest average values are recorded in cluster E (Greece and Cyprus) and only one (39.00%).in cluster D (Germany and Ireland).

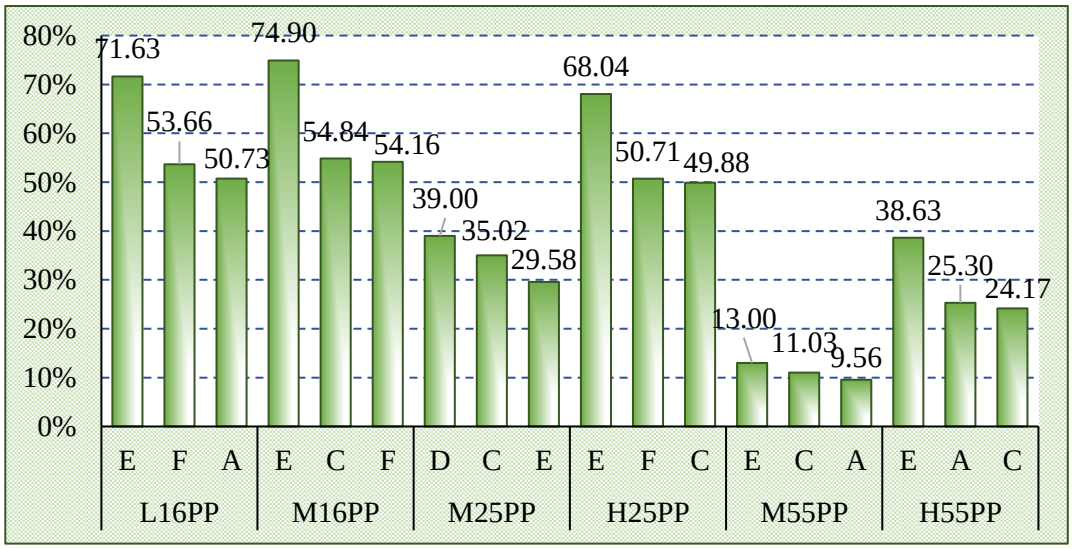


Figure 4. Ranking of the first three clusters according to the shares of GAIT use by individuals for private purposes (PP)

Also, significant shares of GAIT use for private purposes were also recorded in cluster C countries (Denmark, Estonia, Netherlands, Austria, Portugal and Finland), with high average values being recorded for individuals in the 16-24 age group and with USNT

education level (M16PP), of 54.84%, as well as 49.28%, for those with tertiary education and aged 25-54 (H25PP).

Regarding cluster F (Latvia, Lithuania and Slovakia) there were higher average values for individuals in the age group 16-24 with LPLS education level (L16PP), of 53.66%, as well as 50.71%, for those with tertiary education and aged 25-54 (H25PP). On the other hand, while for the population with USNT education level aged 16-24 (M16PP) the average share is 54.16%, for the age group 25-54 (M25PP) it is 22.23%, and for the age group 55-74 (M55PP) it is only 3.57%.

At the opposite pole, the lowest average values of the use of GAIT by individuals for private purposes, with the exception of individuals with USNT education level in the age group 55-74 years (M55PP), were recorded in cluster B (Bulgaria, Italy, Poland and Romania), the average values being between 34.55%, for individuals with USNT education level in the age group 16-25 years (M16PP), 2.16 times less than in cluster E (Greece and Cyprus), and 3.57% for individuals with USNT education level in the age group 55-74 years (M55PP), 3.49 times less than in cluster E. It is worth noting that in the case of individuals with USNT education level in the age group 25-54 years (M25PP) the average value was only 15.78%, 2.47 times less than in cluster D (Germany and Ireland).

Regarding cluster A (Belgium, Czechia, Spain, France, Luxembourg and Slovenia), in terms of the share of GAIT use for private purposes, the average values recorded were in an average area, the most significant being recorded in the case of individuals with LPLS education level, from the age group 16-25 years (L16PP), of 50.73%, and the lowest, of 9.56%, in the case of individuals with USNT education level from the age group 55-74 years (L16PP).

In terms of the use of GAIT by individuals for professional purposes (WP), in the first analysis the average shares ranged between a maximum of 24.43% (Table 5), for the cluster of countries Denmark, Estonia and Sweden and a minimum of 6.62%, for Italy and Romania. This time, by taking into account the age groups (Table 9), the average values ranged between a maximum of 49.90%, a value recorded in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal and Finland) for individuals in the age group 25-54 years and with tertiary education level (H55WP) and a minimum of 0.22%, a value recorded in cluster F (Latvia, Lithuania and Slovakia) for individuals in the age group 55-74 years and USNT education level (M55WP).

Among the six clusters, the three highest average shares of GAIT use by individuals for professional purposes (Figure 5) were recorded in clusters A, C, D and E. In terms of educational level, the highest average values were recorded for individuals with tertiary education level in the age group 25-54 years, followed by those with USNT education level in the age groups 16-24 years and 25-54 years.

At cluster level, in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal and Finland) maximum values were recorded for individuals with USNT education level in all three age groups, as well as for individuals with tertiary education level in the age groups 25-54 years (H25WP) and 55-74 years (H55WP).

Important shares of the use of GAIT for professional purposes were also recorded in cluster E (Greece and Cyprus), of 44.54%, in the case of individuals with tertiary educational level in the age group 25-54 (H25WP) and 20.68%, for those in the age group 55-74 (H55WP), as well as in cluster A (Belgium, Czechia, Spain, France, Luxembourg and Slovenia) of 42.55% and 15.98% for individuals with tertiary educational level in the age groups 25-54 (H25WP) and 55-64 (H55WP), as well as for individuals with USNT educational level in the age groups 16-24 (M16WP), of 17.46%, and 25-54 (M25WP), of 14.09%.

Regarding individuals with LPLS education level using GAIT for professional purposes (L16WP), the highest mean share of 13.28% was recorded in cluster D (Germany and Ireland). Also, in cluster D significant mean values of 23.35% and 13.37% were recorded, in the case of individuals with USNT educational level in the age groups 16-24 years (M16WP) and 25-54 years (M25WP).

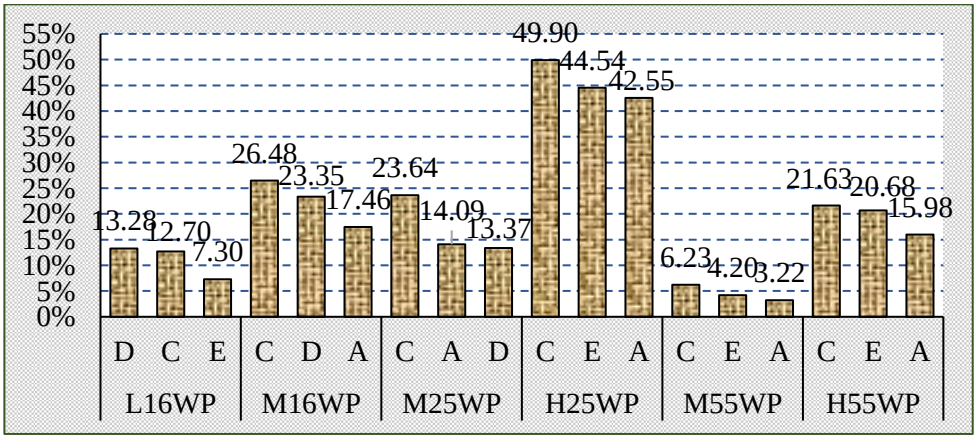


Figure 5 Ranking of the first three clusters according to the shares of GAIT use by individuals for professional purposes (WP)

The lowest values, in terms of the use of GAIT by individuals for professional purposes (WP), were recorded, as in the case of their use for private purposes (PP), in cluster B (Bulgaria, Italy, Poland and Romania), with values ranging between 22.47% in the case of individuals with tertiary educational level in the age group 25-54 years (H25WP), 2.22 times less than in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal and Finland), and 1.44% in the case of individuals with USNT educational level in the age group 55-74 years (M55WP), 4.34 times less than in cluster C.

Regarding cluster F (Latvia, Lithuania and Slovakia), except for individuals with USNT educational level in the age group 55-74 years (M55WP), for whom the average share of

using GAIT for professional purposes was 0.80%, the other values are in the middle range, ranging between 36.86% for individuals with tertiary educational level in the age group 25-54 years (H25WP) and 8.39% for individuals with USNT educational level in the age group 25-54 years (M25WP).

In terms of the use of GAIT by individuals in formal education purpose (FE), by taking into account age groups, the values ranged between a maximum of 60.11%, a value recorded in cluster E (Greece and Cyprus) for individuals in the age group 16-24 years and with USNT education level (M16FE) and a minimum of 1.50%, a value recorded in cluster B (Bulgaria, Italy, Poland and Romania) for individuals in the age group 25-54 years and USNT education level (M25FE).

Unlike the average shares of individuals using GAIT for private or professional purposes, in the case of their use for formal education purposes the differences between age groups are particularly large (Figure 6). Thus, while in the case of the 16-24 age group the lowest share of individuals using GAIT for formal education purposes was 26.06%, a value recorded in cluster B (Bulgaria, Italy, Poland and Romania) for individuals with USNT education level, in the case of the 25-54 age group the highest average share was only 16.01%, a value recorded in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal, Finland) for individuals with tertiary education level, from the age group 55-74 years.

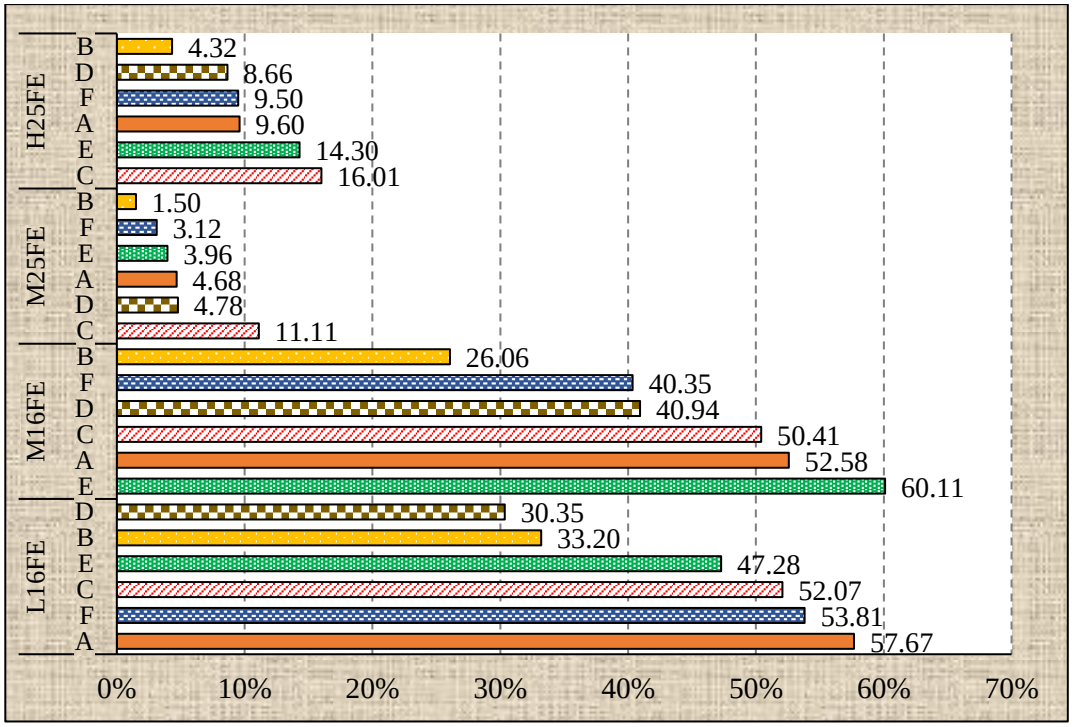


Figure 6. Hierarchy of clusters according to the share of GAIT use by individuals in formal education purpose (FE)

Among individuals in the 16-24 age group, those most interested in using GAIT for formal education purposes were those in clusters A (Belgium, Czechia, Spain, France, Luxembourg, Slovenia) and C (Denmark, Estonia, Netherlands, Austria, Portugal, Finland), both those with LPLS education level (57.67% in cluster A and 52.07% in cluster C) and those with USNT education level (52.58% in cluster A and 50.41% in cluster C). Also, individuals with LPLS education level in cluster F (Latvia, Lithuania and Slovakia), registered a share of 53.81%, and those with USNT education level in cluster E (Greece and Cyprus), registered a share of 60.11%. At the opposite pole, low values were recorded in cluster B (Bulgaria, Italy, Poland and Romania), of 33.20% for individuals with LPLS education level, and 26.06% for individuals with USNT education level..

After the age of 25, data recorded at the level of 2025 highlights a sharp decrease in individuals' interest in using GAIT for formal educational purposes, especially among those with LPLS education level, as well as for those in the 55-74 age group, for whom the data series are of low reliability. In the case of the 25-54 age group, while for those with USNT education level (M25FE) it decreases to values between 11.11% in cluster C and 1.50%, in cluster B, in the case of individuals with tertiary education level (H25FE) the interest in using GAIT in formal education purpose is maintained, although at a lower level than in the case of those in the 16-24 age group, the highest average share, of 16.01%, also being registered in cluster C, and the lowest, of 4.32% in cluster B (Bulgaria, Italy, Poland and Romania).

5. Conclusions

In the first part of the analyses carried out, based on data recorded in 2025, it resulted that the main purpose for which individuals between 16 and 74 years old use GAIT was private, with the highest average share of 36.63% being recorded in the group of states Ireland, Cyprus and Luxembourg. In the second place was professional purpose with a maximum average share of 24.43%, recorded in the group of states Denmark, Estonia and Sweden, and in third place was formal education purpose with a maximum average share of 18.09%, also recorded in the group of states Denmark, Estonia and Sweden. At the opposite pole, the lowest average share of GAIT use by individuals were recorded in the group of states formed by Italy and Romania.

In the second part of the analysis, by taking into account the age groups and education level of individuals, a series of new similarities and disparities emerged between the twenty-four European Union countries included in the analysis.

In terms of the use of GAIT by individuals for private purposes (PP), by taking into account the age groups, at the level of the year 2025, the average shares ranged between a maximum of 74.90%, a value recorded in cluster E (Greece and Cyprus), for individuals in the age

group 16-24 years and with USNT education level, and a minimum of 3.57%, a value recorded in cluster F (Latvia, Lithuania and Slovakia) for individuals in the age group 55-74 years and with USNT education level. Differences in the average shares of the use of GAIT for private purposes resulted, both between the education levels of the individuals and between the age groups, especially between the age group 16-24 years and the others. Within the age group 16-24 years, the differences between the education levels of the individuals did not significantly influence the shares of the use of GAIT for private purposes.

The level of education is a significant differentiating factor between the shares of individuals using GAIT for professional purposes (WP), the highest average values being recorded for individuals in the age group 25-54 with tertiary educational level, of 49.90%, in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal and Finland), of 45.54%, in cluster E (Greece and Cyprus) and of 42.55%, in cluster A (Belgium, Czechia, Spain, France, Luxembourg and Slovenia). The lowest values of the shares of individuals using GAIT for professional purposes were recorded in clusters B (Bulgaria, Italy, Poland and Romania) and F (Latvia, Lithuania and Slovakia).

In terms of the use of GAIT by individuals in formal education purpose (FE), unlike the average shares of individuals using GAIT for private or professional purposes, differences between age groups are significantly large, with the highest shares being recorded for individuals in the 16-24 age group, over 2.5 times higher than in the other age groups. As individuals age increases, the shares of GAIT use for educational purposes decrease exponentially, but remain, to some extent, for individuals with tertiary educational level in the 25-54 age group, especially for those in the countries included in cluster C (Denmark, Estonia, Netherlands, Austria, Portugal and Finland).

Finally, regarding Romania's place, it was included in the first analysis, together with Italy, in the cluster with the worst results in the use of GAIT by individuals. In Romania, in 2025, the shares of GAIT use by individuals were 14.85% for private purpose, 5.24% for professional purpose and only 3.37% for formal educational purpose, while the share of the population with LPLS education level was 24.3%, and with tertiary educational level was only 15.1%. By age groups and education levels, in Romania, in the age group 16-24 years, the share of GAIT use in formal education purpose was 21.09% for those with LPLS education level and 25.84% for those with USNT education level. In the age group 25-54 years, the share using GAIT was only 0.15%, in the case of those with USNT education level, and only 1.43% in the case of those with tertiary education level.

References

[1] Bick, Alexander, Blandin, Adam and Deming, David, (2025), The State of Generative AI Adoption in 2025, On the Economy, Federal Reserve Bank of St. Louis.

[2] Pearson, Andrew, (2024), Creativity: Firing on all generative AI cylinders, *Journal of Digital & Social Media Marketing*, **12**, issue 1, p. 52-64.

[3] Bick, Alexander, Blandin, Adam and Deming, David, (2025), The Impact of Generative AI on Work Productivity, On the Economy, Federal Reserve Bank of St. Louis.

[4] Calvino, Flavio, Haerle, Daniel and Liu, Sarah, (2025), Is generative AI a General Purpose Technology?: Implications for productivity and policy, No 40, OECD Artificial Intelligence Papers, OECD Publishing.

[5] Fioravante, Rosa and Vaccaro, Antonino, (2025), Personalism in Generative AI Deployment: Deciding Ethically When Human Creative Expression is at Stake, *Humanistic Management Journal*, **10**, issue 3, p. 387-409.

[6] Al-Falahat, Ala'a M., (2025), Artificial Intelligence tools perceptions: A survey to measure the Perceptions of Engineering Students, *International Journal of Innovative Research and Scientific Studies*, **8**, issue 3, p. 3344-3355.

[7] Abri, Maimoona Al, Mamari, Abdullah Al and Marzouqi, Zakria Al, (2025), Exploring the implications of generative-AI tools in teaching and learning practices, *Journal of Education and e-Learning Research*, **12**, issue 1, p. 31-41.

[8] Osondu, James, (2024), Benefits of Using Artificial Intelligence Tools in Education, *Nauchni trudove*, issue 1.

[9] Juraj, Fabus, Miriam, Garbarova, Lukas, Vartiak and Ludmila, Mitkova, (2025), The Use of AI Tools in Managerial Education, *Management Theory and Studies for Rural Business and Infrastructure Development*, **47**, issue 2, p. 251-259.

[10] Petrescu Irina Elena & Gole Iulian & Balu Florentina Olivia & Sabie Oana Matilda, 2025. "**The Role of AI Tools in Increasing the Efficiency of Research and Teaching**," Proceedings of the International Conference on Business Excellence, Sciendo, vol. 19(1), pages 656-663.

[11] Taeihagh, Araz, (2025), Governance of Generative AI, *Policy and Society*, **44**, issue 1, p. 1-22. https://econpapers.repec.org/article/ouppolsoc/v_3a44_3ay_3a2025_3ai_3a1_3ap_3a1-22..htm

[12] Rebekka Schwesig & Irina Brich & Jürgen Buder & Markus Huff & Nadia Said, 2023. "**Using artificial intelligence (AI)? Risk and opportunity perception of AI predict people's willingness to use AI**," Journal of Risk Research, Taylor & Francis Journals, vol. 26(10), pages 1053-1084, October.

[13] Kim, Jhonghee and Kim, Hyungjoon, (2025), The use of generative AI tools in design work: Motivation and decision-making process of users, *Edelweiss Applied Science and Technology*, **9**, issue 4, p. 74-82

[14] Leonardo Gambacorta & Tullio Jappelli & Tommaso Oliviero, 2025. "Exploring household adoption and usage of generative AI: new evidence from Italy," BIS Working Papers 1298, Bank for International Settlements.

[15] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_Standard_Classification_of_Education (ISCED)

[16] https://ec.europa.eu/eurostat/databrowser/view/edat_lfs_9903__custom_19879848/default/table Population in private households by educational attainment level (%), 20-01.2026

[17] https://ec.europa.eu/eurostat/databrowser/view/isoc_ai_iaiu/default/table?lang=en&category=isoc.isoc_i.isoc_ai Individuals - use of generative AI tools, 20-01.2026

[18] Johnson, S.C., Hierarchical clustering schemes, Psychometrika 32, 241–254 (1967)

[19] D'Andrade, R.G. U-statistic hierarchical clustering, Psychometrika 43, 59–67 (1978)

[20] García-Escudero, L. A., Gordaliza, A., Matrán, C., & Mayo-Iscar, A. (2010). A review of robust clustering methods. *Advances in Data Analysis and Classification*, *4*(2–3), 89–109.

[21] Murtagh, F., & Legendre, P. (2014). Ward's hierarchical agglomerative clustering method: Which algorithms implement Ward's criterion? *Journal of Classification*, *31*(3), 274–295.

Bibliography

Abri, Maimoona Al, Mamari, Abdullah Al and Marzouqi, Zakria Al, (2025), Exploring the implications of generative-AI tools in teaching and learning practices, *Journal of Education and e-Learning Research*, 12, issue 1, p. 31-41.

Aisha Zahid Huriye, 2023. "The Ethics of Artificial Intelligence: Examining the Ethical Considerations Surrounding the Development and Use of AI," American Journal of Technology, Global Peer Reviewed Journals, vol. 2(1), pages 37-44.

Al-Falahat, Ala'a M., (2025), Artificial Intelligence tools perceptions: A survey to measure the Perceptions of Engineering Students, *International Journal of Innovative Research and Scientific Studies*, 8, issue 3, p. 3344-3355.

Bick, Alexander, Blandin, Adam and Deming, David, (2025), The Impact of Generative AI on Work Productivity, On the Economy, Federal Reserve Bank of St. Louis.

Bick, Alexander, Blandin, Adam and Deming, David, (2025), The State of Generative AI Adoption in 2025, On the Economy, Federal Reserve Bank of St. Louis.

Bogoslov, Ioana Andreea and Stoica, Eduard, (2024), GENERATIVE AI ADOPTION IN TEACHING PROCESSES: ANALYZING INSIGHTS FROM CHATGPT, *Revista Economica*, 76, issue 3, p. 7-20.

Calvino, Flavio, Haerle, Daniel and Liu, Sarah, (2025), Is generative AI a General Purpose Technology?: Implications for productivity and policy, No 40, OECD Artificial Intelligence Papers, OECD Publishing.

D'Andrade, R.G. U-statistic hierarchical clustering, Psychometrika 43, 59–67 (1978)

Eduard-Mihai, Manta, Cristina, Geambasu Maria and Ioana, Birlan, (2025), Mapping AI Adoption across Europe: A Cluster Analysis of National Responsibility, *Proceedings of the International Conference on Business Excellence*, 19, issue 1, p. 1532-1545.

Fioravante, Rosa and Vaccaro, Antonino, (2025), Personalism in Generative AI Deployment: Deciding Ethically When Human Creative Expression is at Stake, *Humanistic Management Journal*, 10, issue 3, p. 387-409.

García-Escudero, L. A., Gordaliza, A., Matrán, C., & Mayo-Iscar, A. (2010). A review of robust clustering methods. *Advances in Data Analysis and Classification*, *4*(2–3), 89–109.

Horia Alexandru Modran & Doru Ursuțiu & Cornel Samoilă, 2024. "Using the Theoretical-Experiential Binomial for Educating AI-Literate Students," Sustainability, MDPI, vol. 16(10), pages 1-20, May.

https://ec.europa.eu/eurostat/databrowser/view/edat_lfs_9903__custom_19879848/default/table Population in private households by educational attainment level (%), 20-01.2026

https://ec.europa.eu/eurostat/databrowser/view/isoc_ai_iaiu/default/table?lang=en&category=isoc.isoc_i.isoc_ai Individuals - use of generative AI tools, 20-01.2026

https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_Standard_Classification_of_Education (ISCED)

Johnson, S.C., Hierarchical clustering schemes, Psychometrika 32, 241–254 (1967)

Juraj, Fabus, Miriam, Garbarova, Lukas, Vartiak and Ludmila, Mitkova, (2025), The Use of AI Tools in Managerial Education, *Management Theory and Studies for Rural Business and Infrastructure Development*, 47, issue 2, p. 251-259.

Kim, Jhonghee and Kim, Hyungjoon, (2025), The use of generative AI tools in design work: Motivation and decision-making process of users, *Edelweiss Applied Science and Technology*, 9, issue 4, p. 74-82

Leonardo Gambacorta & Tullio Jappelli & Tommaso Oliviero, 2025. "Exploring household adoption and usage of generative AI: new evidence from Italy," BIS Working Papers 1298, Bank for International Settlements. https://ideas.repec.org/p/bis/biswps/1298.html

Murtagh, F., & Legendre, P. (2014). Ward's hierarchical agglomerative clustering method: Which algorithms implement Ward's criterion? *Journal of Classification*, *31*(3), 274–295.

Osondu, James, (2024), Benefits of Using Artificial Intelligence Tools in Education, *Nauchni trudove*, issue 1.

Pearson, Andrew, (2024), Creativity: Firing on all generative AI cylinders, *Journal of Digital & Social Media Marketing*, 12, issue 1, p. 52-64.

Petrescu Irina Elena & Gole Iulian & Balu Florentina Olivia & Sabie Oana Matilda, 2025. "The Role of AI Tools in Increasing the Efficiency of Research and Teaching," Proceedings of the International Conference on Business Excellence, Sciendo, vol. 19(1), pages 656-663.

Rebekka Schwesig & Irina Brich & Jürgen Buder & Markus Huff & Nadia Said, 2023. "Using artificial intelligence (AI)? Risk and opportunity perception of AI predict people's willingness to use AI," Journal of Risk Research, Taylor & Francis Journals, vol. 26(10), pages 1053-1084, October.

Şahin Gökçearslan & Elif Esiyok & Kemal Gurkan Kucukergin, 2025. "Understanding the intention to use artificial intelligence chatbots in education: The role of individual innovativeness and AI trust among university students," Journal of Computational Social Science, Springer, vol. 8(3), pages 1-23, August.

Sangbum Kang & Yongjoo Choi & Boyoung Kim, 2024. "Impact of Motivation Factors for Using Generative AI Services on Continuous Use Intention: Mediating Trust and Acceptance Attitude," Social Sciences, MDPI, vol. 13(9), pages 1-18, September.

Stan Marian & Ciobotea Mihai & Voda Adina Maria & Badea Doina Liliana, 2025. "Artificial Intelligence Landscape in the European Union. A Comparative Study," Proceedings of the International Conference on Business Excellence, Sciendo, vol. 19(1), pages 3432-3445.

Taeihagh, Araz, (2025), Governance of Generative AI, *Policy and Society*, 44, issue 1, p. 1-22.

Tallberg, Jonas & Lundgren, Magnus & Geith, Johannes, 2024. "AI regulation in the European Union: examining non-state actor preferences," Business and Politics, Cambridge University Press, vol. 26(2), pages 218-239, June.

ACCOUNTING-FINANCIAL ANALYSIS: AN AMPLIFYING FACTOR IN FINANCIAL REPORTING KNOWLEDGE GROWTH

Marilena Roxana ZUCA[1]

Abstract:
To identify a potential financial fraud, it is necessary to understand the financial-accounting information contained in the financial statements, as well as how to separate it into economic and financial indicators capable of attesting to both the entity's patrimonial existence and performance, as well as the anomalies caused by the financial fraud. The goal of this research is to examine the possibilities for detecting fraud using a set of indicators calculated from financial accounts, some of which demonstrate the predicted cognitive value over time.
In this respect, the research problem was defined as the application of economic and financial analysis *as a relevant tool for the concrete investigation of financial fraud*, as well as empirical data from accounting professionals. The conceptual method was turned into an applied field by abstracting fraud in a language specific to financial and accounting information and palletising acts in a system of indicators known as the *Guideboard for the Financial Analysis of Fraud.*
This academic tool was put through a statistical method of inquiry to confirm its own beliefs by carefully examining the views of the accounting experts at CECCAR regarding the significance of certain economic and financial analysis indicators.
The general research topic, to which this scientific approach aims to provide a response, is as follows: To what degree does financial-accounting information provided by accounting and capitalised by economic-financial analysis contribute to the improvement of an entity's credibility if it is valuable to individuals interested in its economic performance and is not influenced by fraud?

Keywords: accounting, economic and financial analysis, financial information, annual financial statements, financial fraud, creative accounting.

JEL Classification: M41 – Accounting

1. Introduction. The pragmatic value of systematising financial and accounting information from financial reports

[1] PhD Associate Professor, Romanian-American University Bucharest, Romania, e-mail: marilena.roxana.zuca@rau.ro

The scientific approach sought to validate the following research hypothesis: Financial accounting information, the finished product of the professional accountant's activity, is positively associated with economic and financial analysis, because it can be harnessed innovatively through palletising actions in a system of economic and financial indicators, able to signal a potential fraud by manipulating revenues, associated with the financial performance of an enterprise.

The scientific approach was developed and aimed toward the need to apply methods for analysing the quality of financial and accounting information provided through financial statements, which can lead to the revelation of financial fraud. Against the backdrop of the analysis of financial scandals, but also of the typology of fraud, being aware that the financial performance of an enterprise may be affected by fraud, both in the sense of positive cosmetization (overvaluation of income or undervaluation of expenses) and in the sense of negative cosmetization (depreciation of income or overvaluation of expenses), the research study only addresses the side of fraudulent financial reporting built deceit (investors, lenders, suppliers, customers or employees). Financial reporting is the most representative type of systematised financial-accounting information. The regulated yearly financial statements are the most often used type of financial report. Annual financial statements are financial reporting papers that show the amount and quantity of an organization's real and monetary flows at a specific point in time, resulting from its interactions with the outside world and its internal operations, respectively.

Thus, annual financial statements must provide information about an enterprise's financial situation, performance, and cash flows that can be used by a wide range of consumers to make economic decisions. The financial statements are also designed to reflect the results of the undertaking's management, such as how the resources entrusted to it were employed (Feleagă N., Malciu L.,2002) [1]. According to the International Financial Reporting Standards (IFRS), annual financial statements are summary accounting documents that provide information about the economic entity's financial position, performance, and change in financial position, which is useful in the process of making economic decisions. According to IAS1, "presentation of financial statements" refers to "the set of summary accounting documents that are published for the purpose of ensuring financial information of third parties interested in the financial position and performance of the economic entity, which includes the balance sheet, profit and loss account, cash flow table, statement of change in equity, notes, and explanatory statements."" (Ionaşcu I., 2003) [2]. We conclude that Romanian economic entities' annual financial statements contain a structured collection of information, including a balance sheet, profit and loss account, statement of changes in equity, statement of assets, statement of cash flows, and annexes. *The balance sheet*, a summary accounting document that summarizes the enterprise's assets, liabilities, and equity at the conclusion of the fiscal year, serves as the beginning point for economic and financial analysis. The balance sheet can be used to examine the enterprise's assets and liabilities, patrimonial existence, and financing sources.

When they are not included in the explanatory notes (financial statement annexes), balance sheet items of the type of receivables and liabilities are employed in economic and financial analysis through indicators that can expose creative accounting procedures). *The profit and loss account*, which is a part of the annual financial statements, is the primary source for evaluating the economic entity's performance since it covers all of the activities conducted in terms of value flows, beginning with the management period's revenues and expenses.

The use of income and expense items in the form of economic and financial indicators in the profit and loss account not only make it easier to understand how well the business is performing, but they also reveal innovative accounting methods that, if not disclosed in the explanatory notes (financial statement annexes), may indicate the presence of financial fraud.

The financial analyst's imaginative thinking dictates the types of economic and financial indicators related to the balance sheet and profit and loss account that can be utilized in the process of identifying fraudulent financial statements. For this reason, a system was created, presented, and explained in this study in a Guidance Board.

The changes in equity represent according to M. Lesconi, A. Frumusanu and A. Breuer (2013) [3], "the increase or decrease in net assets over the period as a result of capitalized gains and losses, including revaluation discrepancies, exchange rate fluctuations, and dividends that are directly recorded as changes in equity along with capital transactions and payments to economic entity owners". The risk of overestimating equity is the main justification for analyzing changes in equity to support an advantageous position on the market, particularly for public corporations.

The statement of cash flows is frequently thought to be the most precise summary document in the format of annual financial statements (Magnan M. 2002) [4]. This reporting document's usage of financial data is crucial for assessing an organization's medium-term and long-term stability as well as its financial health. Using professional judgment as the foundation for classifying operations, there are two fundamental ways to manipulate operational activities in the cash flow statement: raising cash flow from operating activities and decreasing cash flow from operating activities.

The simplest approach for influencing cash flow is thought to be increasing cash flow from operating operations by stagnating or, at most, slowing down the rate of debt payments. To help users correctly understand the information in the balance sheet, the profit and loss account, and, when applicable, the statement of changes in equity or the statement of cash flows, *the notes* to the financial statements should include thorough explanations of accounting policies and any notable changes in assets and liabilities.

In the same way M. Lesconi, A.Frumușanu și A. Breuer,(2013) [3], show that "To develop and complete the information shown in the balance sheet, profit and loss account, cash flow statement, and statement of changes in equity, explanatory notes to the yearly financial statements are prepared". The management self-declarations are included in this appendix. When it comes to using creative accounting procedures in a transparent manner, their

significance is overwhelming since they allow any interested user to make accurate decisions.

Between creative accounting and fraud committed in the preparation and communication of financial statements, the economic-financial analysis of the data and information contained in the financial statements is interposed, as a means of enhancing the boundary between the two. The analysis aspects, materialized in the component elements of the financial statements and in the ways of action to detect fraud, are described synoptically in *Table 1*.

Table no. 1. Economic and financial analysis components that are utilized to distinguish between accounting fraud and creative accounting

Components of financial statements	**Creative accounting techniques included**	**Elements of economic and financial analysis of the intended purpose**	**Possible accounting fraud actions**
Balance sheet	-valuations or revaluations of assets -assignments of receivables -optional amortization plan -sale with option to repurchase fixed assets or inventories	overvaluation of assets or undervaluation of liabilities	-Fictitious transfers, recording increases in assets without supporting documentation, failing to record liabilities, and failing to record asset outflows -Inadequate explanation of the innovative accounting methods employed and their effects on the balance sheet's assets and liabilities in the annexes (explanatory notes)
Profit and loss account	-Recording advanced income around current income. -capitalisation of expenses with inventories or investments brought into operation -remission of debt -the establishment of provisions. - Depreciation of inventories or receivables -sale with the possibility to	overvaluation of assets or undervaluation of liabilities	- Failure to record income or record fictitious documents regarding income and expenses -Omission of detailed description in the annexes (explanatory notes) of the creative accounting techniques used and their influences on the performance reflected in the profit and loss account

Components of financial statements	Creative accounting techniques included	Elements of economic and financial analysis of the intended purpose	Possible accounting fraud actions
	subsequently repurchase fixed assets or inventories. -option for the most advantageous way of discharging inventories from management (FIFO, LIFO)		
Statement of changes in equity	Overvaluation of tangible assets and integration into revaluation reserves	Overvaluation of equity	Intentionally favourable revaluation of equity elements (untruthful) without explanation in the notes to the financial statements
Cash flow statement	-keeping track of all transactions, from investing to operating -using cash rather than accrual accounting to report income	using the flexibility of accounting law in classifying cash flows	Using the flexibility of accounting law without this option being explained in the notes to the financial statements
Fixed assets situation	-using various techniques to record depreciation over time -valuing buildings, land, or other tangible assets at entry or through forced revaluation to alter depreciation costs	using the flexibility of accounting law in depreciation and valuation policy	Using the flexibility of the accounting law without this option being explained in the annexes of the financial statements

Source: own research

2. Literature review

The general definition of economic and financial analysis based on financial statements is the methodical examination of its constituent parts in order to derive information that is helpful in making financial decisions. Al-Khoury, A., Al-Shattarat, H., Alghazzawi, R., Haddad, H. (2023) [5], consider the analysis of annual financial statements as having "the fundamental function of converting data into useful information" ". Tabără, N., Horomnea, E., Toma, C. (2012) [6] claim that the primary purpose of yearly financial statements is to

give stock market investors relevant information for decision-making. Since Romanian accounting is still heavily controlled, we believe that the primary purpose of financial statements is to inform associates/shareholders, employees, and, finally, state control organisations. We think that other business partners also use financial statements to make decisions, but the legally required format of these reports does not give them the best information they require, so they turn to specialised financial and economic analysis services, particularly short- and medium-term forecasting. In this regard, we agree with some authors who believe that while some accounting data can be used in a "raw" state during the decision-making process, many of them reveal their informational value after the economic-financial analysis process, which enables the creation of a system of indicators to assess financial and economic performance, a company's health, and possible financial fraud (Mihalciuc, 2009) [7].

We believe that the performance of companies is an important topic in the complex field of economic and financial analysis. Performance is defined as a unique accomplishment in a field of activity by the Romanian language's explanatory dictionary. Accounting theories take a more or less holistic approach to performance. Performance and results are often tightly related, and the accounting result is considered an "indicator" of this association.

(Wang, J., Yung, K.,2011) [8]. The "starting point in profitability-based evaluation methods" (Moskwa-Bęczkowska, D., Reczyńska, J., 2023) [9] is profit maximisation, which is the most common way to describe a company's performance. The drawbacks of the accounting result become "misleading" or apparent over time as a result of the implementation of accounting policies (Dănescu, T., Prozan, M., Prozan, R.D., 2014) [10] *and* the changes in the objectives of business owners have imposed certain redirections in the approaches of specialists. Financial profitability is the ultimate objective of any firm in this evolving environment, and it is also a necessary prerequisite for an enterprise's survival on the market in a competitive economy (Dănescu, T., Prozan, M., Prozan, R.D., 2014) [10]. The business's economic performance serves as an indicator of its level of competitiveness and encompasses not just financial outcomes but also changes in equity, which are concretised in the achievement of the enterprise's strategic development goals. An intriguing categorisation of the various analyses and metrics used to assess an organization's success is available at Burns, N., Kedia, S. (2006) [11]. These scholars believe that gross profit (before taxes), return on invested capital, customer satisfaction, employee satisfaction, and customer profitability are the most important measures of outcomes. In this context, we orientated the scientific approach to the field of economic analysis, beginning with the general notion that any economic activity implies the existence of relationships (interactions) between economic phenomena, and that these relationships are conditioned by a number of interdependent parameters.

When economic-financial analysis identifies and explains the sources of occurrences, highlights their linkages, and forecasts the evolution of predetermined parameters, it takes on a scientific quality. Additionally, it combines in a unique way, deductive reasoning (from

the general to the particular) with inductive reasoning (empirical study that examines reality and develops general principles). In order to achieve this, economic-financial analysis uses a numerical language that is valued mathematically to abstract economic events. This form of abstraction brings us closest to economic reality, but only to the extent that the premises (the financial - accounting information contained in the financial statements) are not falsified.

3. Research methodology

From the perspective of scientific research methodology, traditional research methods were applied: systematic and structured analysis, statistical surveys based on questionnaires, synthesis, induction and deduction, analogy and comparative analysis, and survey-based statistical methods. It was concluded that, by constructing a statistical model to facilitate the analysis of interdependence and causality relationships, a series of answers can be provided regarding the laws governing the phenomenon of financial fraud, with the possibility of extrapolating, generalizing, or even predicting the existence and consequences of fraud in financial statements. To assess the relevance of financial and accounting information in detecting financial fraud, as well as to determine its correlation with the economic performance of companies, whether or not affected by fraud, a statistical survey method was employed to assess the perceptions of specialists in the field (CECCAR-member certified public accountants with relevant experience of over 10 years in accounting expertise and audit, particularly in criminal cases). In the discussion regarding the economic performance of enterprises, the calculation of a system of economic and financial indicators was addressed analytically and descriptively, using the comparison method, both by difference (absolute values) and by ratio (relative values or percentages).

In addition, an economic and financial analysis was conducted to aggregate the system of indicators directly or indirectly correlated with factors influencing fraud in financial statements and to assess their relevance within the broader context, using a comparative analysis across time and space.

4. Vulnerability of the quality of financial and accounting information to various users. Implications and complications regarding the development and communication of financial reports.

Based on the information contained in the annual financial statements, a user can make economic decisions for, at least, the following situations: selling or purchasing goods or services; maintaining and/or increasing the company's capital; maintaining and/or increasing the company's solvency and financial autonomy; granting, restricting or canceling loans depending on the company's degree of financial indebtedness; increasing or terminating commercial contracts; establishing the company's compliance with respect to the taxation of financial results or dividends. We believe that the different users of

financial and accounting data determine how creative accounting approaches are used to manipulate the qualitative aspects of data. We will examine the accounting mechanisms that impact certain positions in the financial statements in relation to the interests of the most significant users in order to further identify a model of indicators capable of reasonably detecting the existence of creative accounting elements in fraudulent financial statements. We emphasise that when these inventive accounting methods are not revealed in the financial statements that are provided to the user, they turn into fraud.

From the perspective of the user of financial accounting information, accounting fraud can occur in the following stages of the accounting information life cycle:

1. In the preliminary phase of preparing supporting documents for accounting purposes.

2. In the accounting recording phase of transactions, either based on false supporting documents or without the preparation of apparently legal supporting documents.

3. In the phase of communicating accounting information through financial statements available to interested users.

The first two phases are not related to creative accounting techniques, which constitute individualized criminal acts (forgery and use of forgery). Creative accounting techniques are specific to the production of financial - accounting information, which has materialized through the favorable interpretation of the existing legislation for the enterprise, for the way in which transactions reflected in legally drawn up documents are recorded in accounting, without violating the applicable law. If these legislative interpretations, based on professional expertise of the producer of financial-accounting information, are transparently described in accounting policies and then brought to the attention of accounting information users within the framework of financial reporting, there is no doubt that we are not dealing with accounting fraud. In this case, we believe that the responsibility for ensuring the application of the qualitative qualities of financial - accounting information is shared by the producer and user of this information. By providing an accurate description of its accounting policies, the first guarantees that the financial accounting information is understandable, and the second must take on the responsibility of knowing how to take advantage of the financial accounting information's content, either through the use of specialised consulting or its own technical expertise. However, we can declare that we are in a fraud situation if innovative accounting methods (Table 2) are employed and these methods are not founded on explicit and comprehensive accounting policies that are made known to the user of financial accounting information within the framework of financial reporting. The illegal activity manifests itself in the distribution of fraudulent financial statements that are constructed using inventive accounting methods without the user of financial accounting information being aware of them. In this instance, outlining the intention to mislead the user, the financial-accounting information becomes vulnerable even though it is fundamentally correct. This is because the user of accounting information makes potentially harmful decisions without knowing the true method of its construction,

decisions that he would not have made if he had known that the financial statements that were communicated to him contained creative accounting.

Table no. 2. An examination of innovative accounting strategies that leave financial and accounting data vulnerable in order to satisfy the needs of different users

Interested user	**The interested manifested by the user**	**Creative accounting techniques that make financial - accounting information vulnerable**
Investors	The information that guarantees the investor's comfort regarding the return on investment and the inherent risk involved is of interest to the investor. In this regard, he is interested in the quality of the client portfolio as well as the changes in turnover, net profit, and dividends paid out.	-accounting for revenue from sales of goods/services before delivery of goods/services, and -accounting in the current financial year for the production obtained or related products/services and subsequent financial years -inflation of mutual services/profits within the group, - estimation of provisions, entitlements, etc.
Creditors	In order to reassure creditors that the loans they have been granted will be repaid at maturity together with the associated interest, information is crucial. They are interested in the following in this regard: turnover, ability to pay, fixed asset value, debt, solvency and liquidity, and asset debt ratio, etc.	-recording of expenditure in capitalisation accounts by way of investment, -overvaluation of the economic life of assets, - change of amortization policy, disempowerment by the forced cancellation of a debt -extension of payment terms, - the consolidation of subsidiaries by equivalence or -exclusion from consolidation of over-indebted subsidiaries, etc.
Suppliers	Suppliers require information that gives them confidence that the goods/services delivered/provided will be paid at maturity. This information may include liquidity and solvency, turnover evolution, indebtedness, and expense evolution, etc.	- Income inflation, -overvaluation of expenses, - knowledge of some real estate, -overvaluation or undervaluation of expenses with depreciation of immobilized assets -undervaluation of liabilities and equity, etc.
Clients	For clients, information is important that ensures their comfort that the activity is	- overvaluation of circulating assets

Interested user	The interested manifested by the user	Creative accounting techniques that make financial - accounting information vulnerable
	carried out in accordance with the principle of continuity, especially when the collaboration is long-term. This information can be stock situation, turnover of personnel, situation of fixed assets, etc.	- decrease in claims by adjustments, artificial transactions - the depreciation of some claims, -reclassification of assets held for sale, -overvaluation of the production of goods/services, etc.
Fiscal and other authorities	For the authorities, the information presented is critical for regulating economic activity, establishing budgetary policies, calculating national income, and other statistics. This information can include compliance with legal provisions, calculation and payment of taxes, fees, and legal contributions, etc.	-Transactions with connected parties or related parties - improper capitalisation of expenses, - Change in amortisation policy, - registering taxable income as advance income. - handling of expenditure on uncapitalised investments -Deduction of interest expenses based on the degree of indebtedness, -use of tax facilities without meeting the legal requirements, etc.
Employees	Information is crucial for ensuring that employees are comfortable with the activity's adherence to the principle of continuity, that the organization is stable and profitable, and that it can offer them career opportunities, pensions, and other benefits in addition to sufficient compensation for their labour. This data may include the evolution of profit and turnover, the evolution of the pay fund, and the costs associated with professional training, etc.	-Making provisions, -managing revenue by boosting turnover for supplies of products or services to be supplied or delivered, and decreasing turnover by recording revenue ahead of time, even when the delivery of goods or the supply of services occurred, etc.
Audience	Information on turnover, the evolution of accounts receivable, the evolution of debt, the evolution of profit, and dividends granted may be sources of information generated by the published financial statements. This is because any user in the audience may be	they are similar to those that can affect investors, creditors, suppliers, customers, employees or state authorities.

Interested user	The interested manifested by the user	Creative accounting techniques that make financial - accounting information vulnerable
	interested in the evolution of entities to have an overview of market developments, of a particular field of activity.	

Source: designed and made by author

The techniques used by the company's management in response to external pressure directly reflect the impact that these different users of financial accounting information have on the realisation and communication of financial statements. It is clear that if any creative accounting-specific technique is not used clearly, financial accounting information becomes insecure. For instance, the business runs the risk of defaulting on its debts, which puts pressure on the company's management (Gunny, K., 2010) [12]. Leverage measures external pressure by comparing total assets to total liabilities. We can evaluate the company's loan repayment capacity with the aid of this report. The company's credit risk is also high if it has a lot of debt. This is backed by studies carried out by Huang, S. Y., Lin, C. C., Chiu, A. A., & Yen, D. C. (2020) [13]. They demonstrate that the higher the company's leverage ratio, the greater the likelihood of misleading financial reporting, as it can encourage managers to commit fraud. It is also evident that an investor or lender would not risk losing money if the entity's financial status was such that they would not receive the projected dividend or interest. A supplier would not give higher payment terms if the undertaking was in excessive debt, with the danger of default and implied risk of payment. Additionally, if there had been obvious economic instability, employee turnover, or a significant decline in the assets required for the production to be sold, a client would no longer have signed a long-term contract with the business. These factors together put pressure on management to come up with ways to guarantee the company's survival, especially during a trying time. At first glance, it can appear that these solutions are meant to trick users if they make use of creative accounting strategies. However, an informed user can no longer be seen as a misled user if these solutions are transparent. This is not the case, however, when schemes that require the fabrication of fictitious documents, false transaction records, or other fakes in physical documents or computer files are used instead of inventive accounting procedures that are permitted by the relevant law. In this particular case, we are dealing with accounting fraud that ultimately employs creative accounting strategies to hide the fraudulent activity rather than creative accounting. The primary consequence of employing creative accounting techniques is the concealment of financial fraud, which makes it extremely difficult for users of financial statements to receive a comprehensive picture of the financial results, either due to a lack of accounting expertise or a lack of access to the data and information used to prepare the financial statements. In this scenario, however, the vulnerability of financial and accounting information is directly tied to fraudulent activities committed during the development phase, which are typically

only found through criminal investigations. To adequately substantiate this opinion, we further investigated the possibilities of revealing fraudulent financial statements that also appeal to creative accounting techniques, using as an economic-financial analysis tool, capable of generating an index-guide, capable of fulfilling the overall purpose of the research.

5. Statistical investigation on the efficacy of splitting accounting information in a system of indicators related to the analysis of fraud associated with the performance of companies.

Theoretical claims were strengthened through statistical survey research aimed at the basic construction of a *Guideboard* in economic and financial analysis, the outcome of the creative action of palletising the financial indicators contained in the financial statements with practical implications in revealing the fraud associated with the evolution of the financial performance of enterprises, in order to justify the incorrect opinion of generalist labelling of creative accounting as fraud.

5.1. Preliminary actions

We first created a picture of the most well-known indicators that are directly calculated based on the data in the financial statements and have varying degrees of significance in the economic analysis of the performance of enterprises in order to ensure greater accuracy of the results and the effectiveness of obtaining opinions applied, concretely, to a known situation. We have created a three-column structured picture that includes the name of the indicator, the calculation formula, and explanations deemed relevant to be kept in relation to the use of each indicator with a higher degree of calculation complexity. This is done in the overall context of research efforts and for easier consultation, including to prevent potential confusion or momentary inattentions for the interviewees. Because it is the outcome of separating financial and accounting data into groups relevant to the balance sheet parts based on a comprehensive study of the literature related to the research issue, this process of creating the produced picture was generally referred to as splitting. Based on data from the balance sheet and profit and loss account, we created a table of economic and financial indicators that we named the *Guideboard* for the economic and financial analysis of fraud related to the economic performance of businesses. It is displayed in Table no. 3.

Table no. 3. Guideboard for the economic and financial analysis of fraud related to corporate economic performance, based on information from the balance sheet and income statement

	Derivative indicators	**Calculus formula**	**Description**
a.	Rate ale rentabilității totale		

1	Return on Equity (R_f) or ROE	net profit/total equity	The ratio is typically significantly less than one; it measures the efficiency of equity utilization (how many lei in profit is generated for every one leu invested in equity by shareholders).
2	Economic profitability rate (R_e) or ROA	Net profit/total assets	It measures the efficiency of asset utilization (how many lei in profit are generated for every leu invested in the company's assets).
3	Commercial profitability rate (R_c)	Gross profit/turnover	Show the efficience of sales.
4	Rate of profitability of resources consumed (R_{rc})	gross profit/total expenses	Show the capacity of gross profit to cover expenses.
5	The rate of financial return on permanent capital (R_{fcper})	gross profit/permanent capital (own capital + provisions + long-term liabilities)	It shows whether the gross profit covers the financing needs, including in the long term.
6	Total net asset (ANC)	Total asset-total debts	It measures the shareholders' wealth, that is, the debt-free asset.
***b*.**	Operational profitability rates		
7	Profitability rate of operating expenses (%)	cost of goods sold/net sales	It measures whether the costs of the goods sold are covered.
8	Gross margin rate (%)	gross profit (net sales - cost of goods sold)/net sales	It measures how much gross profit returns to a sales unit.
9	Margin rate of operating profit (%)	operating profit (net sales - operating expenses)/net sales	It measures how much operational profit returns to a sales unit.
10	Net profit margin rate (%)	Net profit/net sales	It measures how much net profit returns to a sales unit.

11	Asset rentability (ROA) (%)	net income/ (sold intial assets+endual assets)/2)	It measures the coverage of income assets.
12	Return on equity (ROE) (%)	net income/ (initial balance equity +end equity balance)/2)	It measures the degree of capital coverage from income.
13	Net revolving fund (FRN)	FRN = Kper - Ain, Kper = Kp + Dtl; Permanent Capital - Net Fixed Assets (Permanent Capital=Capital Own+Long Term Debts)	It is the expression of the long-term financial balance and is the surplus of the permanent capital over fixed assets.
14	The Needed revolving fund (NFR)	St + Cr - Dnef that is, stocks+credits-non-financial liabilities, based on the value of turnover,	It shows the sums that the economic body must spend to carry out its production process, excluding the sums allotted to asset financing; the ideal ratio is below 15% (10% - 15%).
15	Treasury balance (T)	T = FR - NFR or Tasset: Tpassive: the liability treasury, which includes current loans and the bank's credit balance; asset treasury, which includes cash available from accounts and home and short-term placements	In the short term, a positive treasury indicates that the financial balance has been reached; however, over time, an abundance of stable resources simply results in their inefficient use, which has detrimental effects on loan repayment, interest payments, and labour and capital compensation.
16	Absolute change in net turnover due to the variation in the number of employees (Ns)	$\Delta C_a / N_s$	Temporal analysis of the income gap generated by the number of employees
17	Absolute change in net turnover due to variation in average labour productivity per employee (W)	$\Delta C_a / W$, where (W= CA /medium no. of employees	Temporal analysis of the income gap generated by the employment productivity gap on employees.

18	Gross margin or added value (Q_a)	$Q_a = C_p + It + C_f + A + P_n$	where Cp: staff expenses, including taxes and duties thereof (CAS, unemployment, health). It: corporate tax and other taxes and fees paid by the firm. Cf: financial expenses (interests, commissions, regularizations, etc.). A: depreciation of fixed assets. Pn: net profit.
19	Degree of vertical integration (GIV)	GIV=added value/turnover	The degree of vertical integration that is closer to 1.00 indicates how well-integrated and resilient the economic unit is, and how less vulnerable it is to changes in the financial crisis, interest rates, and currency rates,etc).
20	Contribution of the human factor to the formation of added value	Employees expenses/added value	It is estimated that a contribution of 50% is good .
21	The contribution of fixed assets to added value (A_{af}):	A_{af} = fixed assets/added value	Calculate how fixed assets contribute to the creation of added value.
22	Rate of financial solidarity (R_{sf})	R_{sf} = equity/turnover	demonstrates the percentage of equity capital covered by income received; the empirical values for this indicator that are regarded as normal are between 55% şi 66%.
23	Capital management rate or cost-effectiveness ratio (R_{gc})	R_{gc} = financial expenses/total sales or turnover	Show the coverage of financial expenses in turnover; The normal value of this ratio is between 1,2% şi 2,5%.
24	The rate of correlation between liquidity requirements and sales (R_{llv})	R_{llv} = fixed assets/total sales	calculates the fixed assets' contribution to the turnover; The rate's usual value fluctuates between 10% şi 25%.

25	Asset return rate (R_{va})	R_{va} = turnover/total asset	Displays the extent to which assets are covered by turnover; The asset's return rate often has a higher value than 1,4.
26	Stock rotation speed (V_{rs})	V_{rs} = sales volume (C_a)/ Average stock of finished goods (St).	Displays the sales rhythm of the supply of commodities. A rotational speed of 6 is considered good.
27	Instant payment capacity (C_{pl})	C_{pl} = available (home and bank accounts) (Disp) - debts (amounts due within a year) (Dts)	Shows the available funds after current debts have been paid. Any positive value of the payment capacity of the economic entity is regarded advantageous.
28	The rate of patrimonial liquidity (R_{lp})	R_{lp} = active assets (Ac)/short-term liabilities (Dts)	Measuring the extent of the current liabilities of assets with immediate capitalization. If the liquidity ratio is at least unitary (R_{lp} = 1.00), then the situation of the economic entity is considered good.
29	Asset liquidity rate (R_{la})	R_{la} = (current assets (Ac) - stocks (St))/short-term liabilities (Dts)	demonstrates how current liabilities are covered by instant availability. For the economic entity to benefit from the circumstances, it is suggested that $R_{la} \geq 1$.
30	Solvency ratio (R_s)	R_s = total capital/total debts	if $R_s > 60\%$, the economic entity has good solvency, also if $Rs < 30\%$ the economic entity is considered incapable of payment
31	General liquidity rate (R_{lg})	R_{lg} = (bank +house+portofolio)/total assets	The activity health indicator expresses the possibility of financing the activity; if this indicator takes over 30%, then it indicates an insufficient use of capital; at the same time, too close to 1% indicates an acute need for liquidity. Empirically normal, beneficial values are between 5 și 25%.
32	Depreciation ratio (R_{dep})	R_{dep} = amortization (A)/fixed assets (imobilizări corporale, Af)	New fixed assets must typically be purchased if the depreciation rate is less than 40% since the current ones are suffering from "moral wear."
33	Total debt ratio (R_{it})	R_{it} = total debts /total capitals	Shows the ratio between the total debt of the entity and the capital invested; if the ratio is less than 50%, the liabilities negatively influence the economic profitability, and if approaching 100%, the investment policy is compromised, due to the insufficient funds of the economic entity.

34	Term debt ratio (R_{iter})	R_{iter} = financial liabilities/own capital	demonstrates that if financial liabilities are more than the amount of equity ($R_{iter} > 1$), they will negatively impact the economic entity, leading to a loss of financial autonomy and insolvency when rates and interest can no longer be met by turnover.
35	Repayment capacity rate (R_{cr})	R_{cr} = financial debts/turnover	Is the economic entity's capacity to pay back the yearly debt from turnover.
36	Treasury rate (R_{trez})	R_{trez} = fiscal debts/turover	If the debts to the state treasury can be repaid within 30 days, then their level relative to the turnover is good; if they cannot be repaid, after 45 days the problems related to interest and penalties begin.
37	Self-financing rate (R_{af})	R_{af} = real estate investments /turnover	For a self-financing capacity to be considered good, the self-financing rate must be more than 50%.
38	Expenditure rate per 100 Lei total revenue	Debts/total income	displays the percentage of realised income that is used to cover expenses.
c.	Business risk analysis ratings (exploitation).		
39	Risk of exploitation (R_e)	the level of turnover fully covering operating expenses/turnover	The amount of turnover that completely covers operational costs is known as the profitability threshold.
40	Safety margin (Ms)	Ms = (turnover - profitability threshold or operating expenses)/ turnover	Show the threshold at which profit can be made.
41	Leverage effect of exploitation (Pe)	Pe= [(Profit year 1 -Profit year n 0) Profit year 0] [(CA year 1-CA year 0)/CA year 0]	Demonstrates how much the gross/net profit will fluctuate if the turnover changes by a percentage between periods; the higher the exploitation lever, the greater the risk of exploitation.
42	Average collection period	365/net sales/(initial balance A/R+ final balance A/R)/2)	Shows the period during which sales receivables are collected on average.
43	Speed of stock rotation	365/cost of goods sold/(initial stock	Shows the average time the stock is sold.

		balance+ final stock balance)/2)	
44	Rotation speed of the flow rates	365/accounts to be paid/(initial stock balance+ final stock balance)/2)	Shows the average period during which the stock debts are paid.
45	Cash conversion cycle	stock rotation speed+average collection period-debit rotation speed	displays the typical amount of time that the business has access to the revenues from stock sales after taxes have been paid.
46	Fixed asset return	Net sales/(initial fixed assets balance+final fixed assets balance)/2)	Displays the typical time frame over which sales cover the fixed assets used in sales.
47	Operating profit volatility (EBIT) (coefficient of variation)	standard deviation of earnings before interest and taxes for multiple time periods	Shows the dynamics of earnings before interest and taxes, illustrating the positive or negative impacts of the variability of exploitation from one period to another.
48	Sales volatility (coefficient of variation)	Average net sales/standard sales deviation for multiple time periods	Display sales dynamics, emphasising the positive or negative effects of the variation of sales from one period to another.
49	Volatility of debt burden	Changes in earnings before interest and taxes as a percentage of changes in sales	Demonstrates the dynamics of sales profitability by highlighting swings in earnings before interest and taxes.
d.	Financial risk analysis rates (leverage effect)		
50	Leverage effect index (1)	total debt (long and short term)/assets	Indicates the extent of the coverage of liabilities in assets.
51	Leverage effect index (2)	total debt (both short-term and long-term) divided by equity	Indicates the degree of coverage of equity liabilities.
52	Interest coverage rate	earnings before interest and taxes/interest expenses	Indicates the coverage of interest expenses on operating earnings without interest and taxes.
53	Operating cash rate	operating cash/current liabilities	It shows how the money made from the exploitation activity will satisfy current responsibilities.

Source: own design based on research made

5.2. Methodological standards in statistical research

We selected a sample of expert accountants at random from the CECCAR Members' Table of September 2025 in order to quantify the quantitative and qualitative examination of the indicators in the *Guideboard*. In order to get accurate and pertinent responses to the topics we are interested in, experience and practical competence are crucial components. For this reason, the visual criterion regarding their age was a choice-oriented initial step. Thus, following several free email conversations in which we presented the scientific objective of the research, we specified the need to be a voluntary participant in this study, subject to practicing the profession of expert accountant for at least 10 years and demonstrating judicial accounting expertise in criminal cases. Using this selection method, we finally managed to disseminate the questionnaire and get the answers from a total of 25 expert accountants with over 10 years of professional experience in this field, of which 12 were male and 13 female, considering that it is sufficient and reasonable to fulfil the purpose of empirical investigation, especially that during the filling-in sessions, there were also collective debates, randomly grouped.

Additionally, we decided that the questionnaire's assessment of respondents' opinions should be limited to two open-ended questions in order to accurately capture, in addition to the research effort beliefs, their agreement or disagreement regarding the significance of certain indicators that best depict an organization's economic performance as well as how they can be used to investigate financial fraud. The Guideboard, which included the 53 previously mentioned indicators, was appended to the questionnaire in order to double check the accuracy and dependability of the responses.

The questionnaire had the following questions:

Question no. 1: Please provide your thoughts on the indicators that enable the description and impact of an enterprise's financial performance and that can be computed using the data in the annual financial statements, on a scale of 1 to 5 (1 being the most important and 5 the least important).

Question no. 2: Please indicate, on a scale of 1 to 5, which of the signs listed in question no. 1, in your opinion, may indicate potential financial fraud in the financial statements based on their correlation with one another.

The statistical survey took 135 minutes to complete, including introductory talks. Each responder had a maximum of 30 minutes to complete the questionnaire and have it collected. Excel was used for response processing, including tabulation, score computation, and graphical visualisation. The score for each indicator or association of derived indicators was calculated by weighting the number of positions on a specific place on a scale of 1 to 5 with the complement to the number 6 (5 for place 1, 4 for place 2, 3 for place 3, 2 for place 4, and 1 for place 5). The responses were also double-checked for thoroughness to

ensure that each place in the hierarchy was covered vertically by at least one variant of the suggested indicator combinations.

5.3. Results, Discussion, and Conclusions

1) All 25 certified public accountants who voluntarily agreed to complete the questionnaire answered the first question regarding the indicators that describe a company's financial performance and can be calculated based on information from the annual financial statements. The summary of the responses is presented in Table 4 and Figure 1.

Table no.4 The summary of the responses –question no.1

No.	Indicator name	5	4	3	2	1	Score
		1	2	3	4	5	ranking
1	Gross margin rate	11	1	2	0	0	65
2	Absolute change in net turnover	0	8	10	0	0	62
3	Added value	4	2	6	0	0	46
4	Loan quality index	0	4	0	0	2	18
5	The Needed revolving fund	2	4	0	0	3	29
6	Degree of vertical integration	0	0	0	0	8	8
7	Economic profitability rate	4	0	0	6	5	37
8	Return on Equity	2	0	0	3	3	19
9	The rate of patrimonial liquidity	1	4	7	7	4	60
10	Leverage effect index	1	2	0	9	0	31
	TOTAL	**25**	**25**	**25**	**25**	**25**	

It was noted that, according to the surveyed accounting experts, the first ten indicators calculated on the basis of the information in the financial statements to describe the financial performance of an enterprise are ranked in order of significance as follows: gross margin rate, turnover rate, patrimonial liquidity ratio, added value, rate of economic profitability, leverage ratio, revolving fund needs, financial strength rate, etc. quality index of claims and degree of vertical integration. An agreement was established (women and men) that at the top of the evaluations of the relevance of indicators are operational profitability rates, followed by patrimonial and treasury rates.

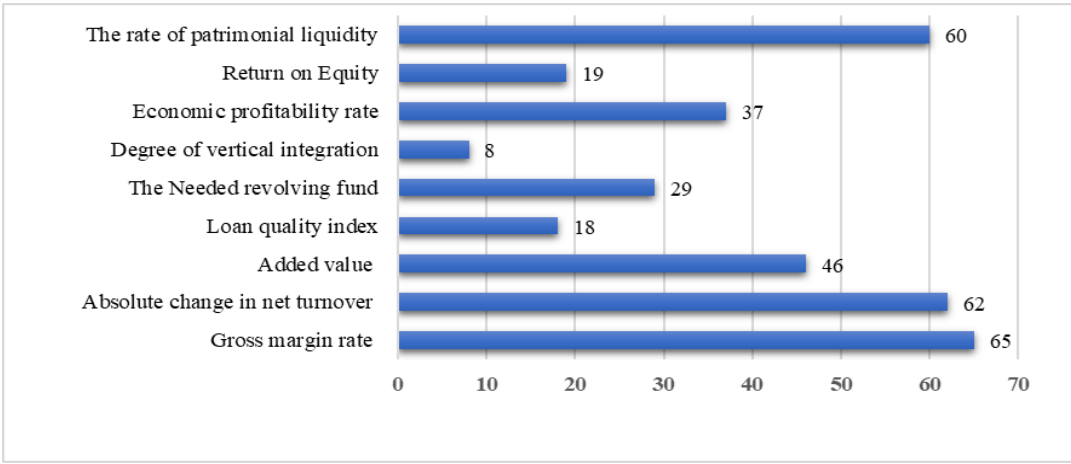


Figure no. 1 Own design based on research made

2) All 25 certified public accountants who voluntarily agreed to complete the questionnaire answered the second question regarding which of the indicators mentioned in question 1, when considered in combination, might suggest possible financial fraud in the financial statements. The summary of the responses is presented in Table 5 and Figure 2:

Table no.5 The summary of the responses -question no.2

No.	Indicator name	5	4	3	2	1	Score
		1	2	3	4	5	ranking
1	Decline in gross margin and increase in debt ratio	9	8	2	1	4	89
2	An increase in revenue and a decrease in the debt collection rate or the debt-to-asset ratio	12	7	4	1	1	103
3	An increase in the economic rate of return and a decrease in the net profit margin	1	2	6	8	7	54
4	Increase in the debt ratio (trade payables) and increase in the revenue collection rate	2	4	11	6	3	74
5	An increase in the return of equity and an increase in the employee turnover rate	1	4	2	9	10	55
	TOTAL	25	25	25	25	25	

Additionally, it was observed that, according to the accounting experts surveyed, a potential financial fraud may be revealed in the financial statements if some of the signs listed in question no. 1 are associated, in the following order of significance: increase in turnover and decrease in the rate of receivables collection, or by raising the debt ratio of assets, decreasing gross margin, and raising the debt ratio, respectively, raise the rate of revenue

collection and raise the rate of trade indebtedness, or raise the financial soundness rate and raise the staff turnover index, lower the rate of economic profitability, and lower the net profit rate.

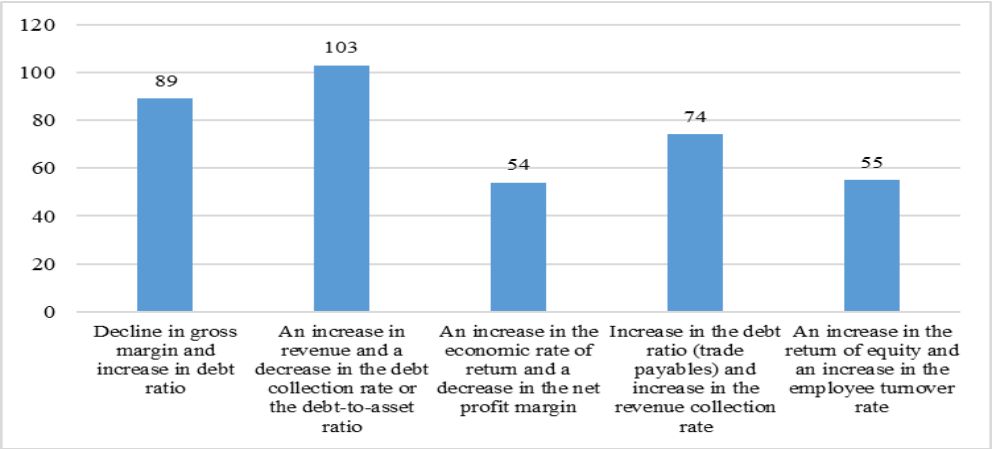


Figure no. 2 Own design based on research made

It follows that a possible financial fraud can be signalled by analyzing the balance sheet and profit and loss indicators, the best rated being the association between the turnover dynamics and the receivables collection dynamics or the gross margin dynamics and the debt ratio dynamics. In case of identification of an increase in turnover that is not accompanied by an increase in the level of receivables related to the sales that make up the turnover, it may be suspected that some revenues may be registered, which, although it determines the assurance of a stable economic performance indicator, does not generate the normal treasury of the activity carried out. In this instance, it is possible to identify income inflation with the express intent of presenting a fictitious economic performance. Overvalued or fictitious expenses that do not impact the treasury for a reasonable amount of time may be suspected in the event of a decline in gross margin and an increase in the debt ratio of assets, even though there is also an increase in the revenue collection rate.

5.4. Conclusions of the statistical survey

We conclude that the debt-to-asset ratio is widely regarded by accounting professionals as the most revealing indicator of potential revenue manipulation, with a direct impact on the assessment of a company's financial performance in cases of suspected fraud.

6. Conclusions

Financial fraud materialized in the construction and communication of fraudulent financial statements is a phenomenon that brings the greatest money losses worldwide. In this context, any efforts to disclose financial fraud can only be of benefit to any enterprise. The cognitive contribution of accounting information in the process of disclosing financial fraud was highlighted innovatively in this study through positive associations with economic and financial analysis and statistical survey. In order to identify the issue of knowledge management in conveying the creation of financial and accounting information about businesses, we used a new methodology in the study. Synthetically, we chose to advance knowledge in this area rather than criticise in order to find ways to enhance the quality of financial and accounting data. We saw this as a fundamental component of a more intricate, visionary construction for the current evolutionary stage of accounting, which can acquire new cognitive valences in conjunction with the scientific nature of economic and financial analysis. This is because accounting professionals' work will soon be primarily focused on the financial and economic examination of automatically processed financial and accounting data. In keeping with this prediction, we have highlighted the weaknesses in the process of creating and disseminating financial statements to different users while simultaneously promoting the utilitarian contribution of systematising financial and accounting information from financial reports, enhancing its qualitative features. By separating actions in a system of indicators known as *Guideboard for financial analysis of fraud*, this conceptual method has been turned into an applied area that encapsulates fraud in a language unique to financial and accounting information. In order to validate its own conviction, this academic tool was subjected to a statistical method of inquiry that looked closely at the opinions of CECCAR accounting professionals regarding the significance of economic and financial analysis indicators that, through creative association, can reveal causal relationships between an enterprise's economic performance and the action of financial statement fraud communicated to users. As a result, we emphasised the significance of combining and separating accounting and financial data into economic and financial indicators, which were creatively structured in the corresponding *Guideboard for financial fraud analysis*. We then verified the survey's relevance. Regarding the significance of certain indicators deemed appropriate to highlight both the economic performance of an enterprise and the possible existence of fraud in financial statements, we have acquired the well-informed opinions of the accounting professionals within CECCAR with pertinent experience performing accounting expertise in criminal cases. We concluded that professional accountants must respond to fraudulent inventiveness by being creative in exposing it based on the opinion survey results.

References

[1] Feleagă N., Malciu L., (2002) , *Accounting Policies and Options*, Economica Publishing House, Bucharest.

[2] Ionaşcu I., (2003), *The Evolution of Contemporary Accounting Theories: Studies on Accounting Paradigms and Practices*, Economica Publishing House, Bucharest.

[3] M. Lesconi, A.Frumușanu și A. Breuer (2013), *Financial accounting*, Economica Publishing House, Bucharest.

[4] Magnan, M. (2002). *Accounting earnings and cash flows as measures of firm performance*. Journal of Financial Statement Analysis**.**

[5] Al-Khoury, A., Al-Shattarat, H., Alghazzawi, R., Haddad, H. (2023). *Creative Accounting Practices and the Credibility of Financial Reports.* WSEAS Transactions on Computer Research, 11, pp.398–403**.**

[6] Tabără, N., Horomnea, E., Toma, C. (2012), *Financial and accounting analysis*, Tipo Moldova Publishing House, Iasi.

[7] (Mihalciuc C., (2009) *Valorificarea informației financiar – contabile în diagnosticul întreprinderii.* Sedcom Libris Publishing House.

[8] Wang, J., Yung, K. (2011). *Do financial restatements affect information asymmetry*? Journal of Financial Research.

[9] Moskwa-Bęczkowska, D., Reczyńska, J. (2023). *Creative Accounting versus Aggressive Accounting – Exploring Specific Dimensions.* Journal of Applied Economic Sciences, 18(4), pp.267–276.

[10] Dănescu, T., Prozan, M., Prozan, R.D. (2014). *Utility of Accounting Information*. Annales Universitatis Apulensis Series Oeconomica.

[11] Burns, N., Kedia, S. (2006). *Performance-based compensation and misreporting*. Journal of Financial Economics.

[12] Gunny, K. (2010). *The relation between earnings management using real activities manipulation and future performance.* Contemporary Accounting Research.

[13] Huang, S. Y., Lin, C. C., Chiu, A. A., & Yen, D. C. (2020). *Fraud detection using fraud triangle risk factors.* Information Systems Frontiers, 22(6), 1407-1427.

Bibliography

Bédard J., (2001), The disciplinary process of the accounting profession: protecting the public or the profession? The Québec experience. Journal of Accounting and Public Policy. 20(4/5).

Neculai Tabără, Emil Horomnea, (2013), Annual accounts in the decision-making process, TipoMoldova Publishing House.

Ristea M., (2006), Balance in the Globalization of Accounting: Appearance and Essence,

in the book *The Accounting Profession in Romania*, C.E.C.C.A.R. Publishing House, Bucharest.

International Financial Reporting Standards (2015), CECCAR Publishing House, Bucharest.

Order No. 1802 of December 29, 2014 – Part I, approving the Accounting Regulations on individual annual financial statements and consolidated annual financial statements, issued by the Ministry of Public Finance, published in the Official Gazette No. 963 of December 30, 2014.

Accounting Law No. 82 of December 24, 1991 (**republished**), enacted by the Romanian Parliament, published in the Official Gazette No. 454 of June 18, 2008, as subsequently amended and supplemented.

Company Law No. 31/1990, republished in the Official Gazette of Romania, Part I, No. 1066 of November 17, 2004, as amended.

Government Ordinance No. 65/1994 on the organization of accounting services and certified public accountants, republished in the Official Gazette of Romania, Part I, No. 13 of January 8, 2008, as subsequently amended and supplemented.

Order No. 2844 of December 12, 2016, approving the Accounting Regulations in accordance with International Financial Reporting Standards, issued by the Ministry of Public Finance, published in the Official Gazette No. 1020 of December 19, 2016.

Ministry of Public Finance, (2002), Accounting Regulations for Business Entities, Economica Publishing House, Bucharest.

FINANCIAL AUDIT BETWEEN ACCOUNTING ACCURACY AND THE VALIDATION OF THE TRUE AND FAIR VIEW

Marilena ZUCA[1]
Alice Emilia ȚÎNȚA[2]
Anda Mihaela LĂCEANU[3]
Georgiana POPA[4]

Abstract

The debate over the accuracy of financial statements and accounting truth from the perspective of financial and accounting information providers on the one hand, and their validation through financial audits on the other, has been and will continue to be a subject that will always generate controversy and opposing views. Often, when errors and malfunctions occur, the role of financial and accounting information producers is ignored, with the blame being placed primarily on those who certify or validate them, namely financial auditors. In this context, trust has suffered the most. Unfortunately, this negative image also hangs over future professionals whose role is to make the profession accountable for the quality of the preparation and validation of financial statements/reports. The motivation for choosing this research topic stems from the desire to study the role of accounting truth and the true and fair view validated by financial auditing. This is why the scientific approach aims to highlight, at all times, the direct link between accounting, financial auditing, true and fair view, and accounting truth. None of these can exist without the other, and respecting the faithfulness and reality of transactions and events carried out within an economic and social entity is, in our opinion, the main prerequisite for regaining trust.

Keywords: financial audit, financial information, fair presentation, true/reality accounting, financial statements quality.

JEL Classification: M41 – Accounting, M42 – Auditing.

1. Introduction.

[1] Corespondent author, PhD, Assoc. Professor, Romanian-American University, Romania, marilena_zuca@yahoo.ro
[2] PhD, Lecturer, external public auditor, The Court of Accounts, Romania, alicetinta@yahoo.com
[3] PhD, director, external public auditor,The Court of Accounts, Romania, andastancioiu@yahoo.com
[4] PhD, external public auditor, The Court of Accounts, Romania, georgianapopa@yahoo.ro

Information is the most valuable commodity of the 21st century. The unprecedented development of the economy and society as a whole has generated an exponential increase in the need for information. Information, especially financial and accounting information, is at the core of the economic life of any entity, influencing its evolution in the business environment. Accounting professionals have a duty to prepare financial statements/reports in accordance with performance, professionalism, and ethical criteria. This way, users will have access to accurate, transparent and credible information. We start from the premise that, in a market economy, the role of the accountant is essential. Accounting communication is at the heart of the decision-making process. The information provided through financial reports is complex and, depending on how it is used, offers a variety of perspectives for analysis. Knowledge is power. The path to knowledge mainly involves deciphering the unknown by discovering new truths. Since ancient times, people have tried to find the path to progress and, implicitly, a certain state of prosperity. In the current economic circumstances, accurately reflecting reality requires the use of a set of information that is subject to constant improvement in terms of accuracy. Most major financial scandals have stemmed from an inaccurate representation of reality through the generalization of error and fraud, or through its cosmetic cover-up. As long as the true picture is not based on the principles of objectivity, fairness, and transparency, the accounting profession will suffer and the social function of accounting will not serve the interests of the many but will be compromised in favor of the few. If information is not the product of ethics and compliance with standards, the truth is "manipulated," misleading investors' perceptions. In order to eliminate, even partially, these dangers, the accounting and auditing professions alike call for the intervention of regulatory and harmonization bodies. Harmonization is not a luxury or a whim, but a necessity resulting from the requirements of users of credible financial statements and quality audit reports to understand and compare the data provided, in a word, to be properly informed. At the same time, in a society often dominated by the interests of the big and powerful, the mechanism for producing information is easily influenced, and mistrust has become almost the norm. In such a relative world, we are witnessing financial scandals, to which we can add economic crises. If, following these findings, we ask ourselves why we need accounting, the answer, in its simplest but truest form, is: each of us is interested in knowing what and how much we own, whether we are referring to personal wealth or the assets of a company. Even if the law did not require accounting to be kept and organized, the need to record economic events is sufficient to establish a record-keeping system based on the actual, real situation. In our research, we found that the setbacks in the economic and business world have often been unfairly associated with the accounting profession, in its capacity as a verifier of truth and communicator of that truth. Let us not forget that ensuring the credibility of accounting data is the responsibility of financial auditors, the "spearhead" of the accounting profession, and perhaps that is why they are most exposed to criticism from the beneficiaries of the information contained in financial statements. We agree that the

current economic difficulties and imperfections are not only due to deficiencies in the legislative and regulatory framework, but especially to the deliberate circumvention of these deficiencies. This is why the financial auditor, acting as an intermediary between the producers of financial and accounting information and its users, is the guarantor of the credibility of accounting truth. That is why we have placed the trinomial accounting – auditing – true and fair view at the centre of our research, concluding that in this field, no one will ever achieve absolute truth. By applying standards, norms, professional reasoning, and professional ethics in good faith, we believe that it is still possible to obtain a representation that is as true to reality as possible. The motivation for choosing this research topic stems from the desire to study the role of accounting truth and fair presentation validated by financial auditing. With the objective of collecting, recording, and transmitting financial information, accounting is the main language of communication in the business world. Our approach considers that the relevance and reliability of financial and accounting information are fundamental to the economic activity of the company and its managerial decisions. Over time, the credibility of accounting as a field has been the subject of debate both within the profession and, particularly, outside it. Considering the major financial scandals and the recent economic crisis, it is easy to understand why the accurate representation expressed by accounting has been seriously questioned. This is why the main objective of accounting must be to obtain a picture that is as close as possible to economic reality. In developing the study, we started from researching accounting truth and the process of validating the true and fair view expressed through financial statements. In our opinion, the credibility of financial information is crucial for the economic environment. The observation and analysis of this field must take into account the interdependent relationships it establishes with the whole range of social and financial events. Therefore, we believe that the research responds to a social need represented by the need to inform users. Through the connection between accounting truth, audit, and fair presentation, we aim to contribute to strengthening confidence in the specialized accounting information system. Over time, accounting professionals have succeeded in developing advanced methods and techniques for recording a company's operations, transactions, and resources. However, we wonder how efficient and accurate such a system of translating reality into numbers is, given the particular complexity of the economic environment. In these circumstances, we consider it appropriate to examine the role of financial auditing in validating the accurate representation of financial and accounting information. The two concepts must be correlated with the notion of performance, since in the competitive environment in which economic entities operate, only continuous monitoring of the accuracy and relevance of accounting data can lead to progress. Furthermore, through such analysis, companies can identify their vulnerabilities and reduce risks. In a world where investors are increasingly skeptical, the confirmation of financial and accounting information creates the conditions for reducing the degree of uncertainty. The subject of the research study is a topical one in the current economic context of globalization. The

substantial volume of information that needs to be processed and the short time available for reporting data for decision-making purposes generate the need for confidence that the financial and accounting information prepared and processed at the entity level is transformed into knowledge that benefits users. Investors can thus find the most important answer for committing their capital, namely the credibility of information, which generates confidence in business. The purpose of our research is to provide some answers regarding accounting truth and fair presentation, the possibilities for validating and valuing accounting information, and tracing the connection between accounting truth, audit, and fair presentation. All of this aims to reasonably assure stakeholders that decisions made based on this information are timely and effective. The research also seeks to highlight the possibilities of providing a true and fair view through financial statements, or in other words, the extent to which the true and fair view expresses accounting truth.

We will specify in context the role of financial auditing in certifying and valuing accounting accuracy. To this end, we have pursued two directions:

- the first direction concerns accounting truth and the true and fair view in accounting;
- the second direction is to highlight the role of auditing in certifying or validating the truth expressed by accounting, in other words, ensuring the quality and relevance of financial and accounting information.

2. Literature review.

a. The conceptual-philosophical approach to truth

Truth has been, is, and will continue to be the subject of discussions that have polarized many philosophical concepts since ancient times, being practically an inexhaustible and ever-relevant topic. However, we can appreciate truth as a fundamental cultural, philosophical, and scientific category with great practical value but also universal theoretical value, expressing the ideal of knowledge in any field of intellectual activity and beyond. In this sense, the philosopher Hacob Paronian believed that it is harder to tell the truth, even harder to listen to it, and hardest of all to make it understood. Truth is the central issue of both epistemology (the theory of scientific knowledge) and gnoseology (the philosophical theory of knowledge), because it guides us towards the search for and acquisition of certain, reliable, and lasting knowledge. The Greek philosopher Parmenides said that there are two paths to knowledge: the path of truth (alteia) and the path of opinion (doxa). In his view, the first path leads us to discover the essence of things, that is, the essence of sensible things, and is the path of certainty and conviction, while the second is the path of uncertainty and doubt, of opinion and appearances that dominate the ordinary mind of people. In classical scientific and philosophical literature, three main theories of truth have emerged, namely: the correspondence theory of truth; the coherence theory of truth; and the pragmatic theory of truth. A general feature of these three theories is that they

define truth by the relationship between the content of a judgment and the content of another object. In other words, truth is an entity that can be described based on the idea that a judgment is true because it has a special relationship either with other judgments already accepted as true, with the world of sensible things, or with people's interests.

b. The accounting approach to truth

Financial and accounting information, is of major significance for management, because it forms the basis for financial decisions and it is therefore particularly important that the data it presents be accurate, in other words, "true." Financial and accounting information must be transparent and accurate in order to enable relevant decisions to be made, at which point it can be said to ensure accounting truth regarding the activity of an economic entity. In this context, the factors that determine accounting truth reside in the following: accounting principles and techniques, accounting standardization, verification of accounting information (by accountants, financial auditors, internal auditors, state control bodies, etc.). For these reasons, British researchers have developed the concept of "true and fair view" associated with financial reporting, which has been translated into Romanian as "exact represenation". The first part of the term has a quantitative, formalized aspect; the second has psychological, ethical, and moral connotations, i.e., informalized (Gray, Coenenberg & Gordon, 1993) [1]. This concept encompasses a quantitative, formalized aspect and a psychological, ethical, and moral connotation, and was recommended by EU Directive 2013/34/EU of June 26, 2013, with the term of French origin "true and fair view" (Colasse, 2007) [2]. Art. 4(3) of EU Directive 2013/34/EU states that "the annual financial statements shall give a true and fair view [...] of the financial position and profit or loss of the undertaking." On the other hand, we can see that the notion of accurate representation is not equivalent to a true and fair view in this directive, because paragraph 22 specifies that "the recognition and measurement of items in the financial statements are based on estimates, judgments, and models rather than on accurate representations." This is natural because the concept does not imply the existence of requirements and rules for the procedure for preparing financial reports. In Romanian, its role is clearly expressed by the term “accounting truth”. The Explanatory Dictionary of the Romanian Language defines truth as "that which corresponds to reality, exists or has actually happened," although we consider that accounting truth is a much broader concept than this. The financial statements, prepared on the basis of data collected and recorded in the accounts, relating to economic events during the reporting period and confirmed by auditors, present the accounting truth of an entity. In this way, users of financial and accounting information can be sure that the information made available to them by the entity's management is accurate and that the decisions made on the basis of this information are correct. From this point of view, accurate information can be considered to be information that allows interested parties to identify a specific event or object in the economic life of the entity. However, it becomes more complicated when it is absolutely necessary to know the object of accounting as a whole and to ensure accurate representation. In this case, accounting, through symbols, applies

specific accounting standards, shapes the processes within the entity and respects the qualitative characteristics of information. The general framework for financial reporting specifies that, in order to be considered an accurate representation, a description must have the following three characteristics: it must be neutral, complete, and error-free. Practitioners in all fields know that perfection can sometimes be achieved, but accounting truth based on accounting principles makes it possible to consider that the information presented in financial reports reflects the reality of the facts and events taking place within the entity. It should be noted that maximizing the quality of financial and accounting information must be the main objective of accounting and, therefore, the information presented in the financial statements can only be recognized by users as true if it is confirmed by an independent financial auditor. In this context, auditing becomes the most important factor in ensuring accounting truth.

3. Research methodology.

Methodologically, the research is mixed, theoretical-descriptive, and the topic was approached from an ethical and positivist perspective. The approach is based on multidisciplinary research that includes concepts and theories from accounting, finance, auditing, taxation, and law. The areas researched include both a qualitative and a quantitative approach. The qualitative approach was used to generate a detailed picture of the concepts of accounting truth and fair presentation, and to establish the role of auditing in validating them. The quantitative analysis was used to complement and substantiate the qualitative approach, using systematic, rational, and grouped sampling, with the sample size being determined in relation to the subject of the study. As regards the source of data, we used databases such as those of the Chamber of Financial Auditors of Romania (CAFR), the Public Supervisory Authority for Statutory Audit (ASPAAS), the Ministry of Public Finance (MFP), the National Institute of Statistics (INS), the International Federation of Accountants (IFAC), and Eurostat. The methods used in the research include observation, comparison, statistics, and specific analysis methods. The data sources are official reports, normative acts, and websites of professional associations and regulatory authorities.

4. Accounting truth/accuracy – the basis of a true and fair view.

4.1. Trust in accounting truth/accurancy

Accounting truth is ensured by: the entity's accountants and management; specific rules and regulations; auditors and experts who monitor and assess compliance with accounting rules and regulations.

Schematically, the factors that influence and ensure accounting truth/accuracy are presented in Figure 1.

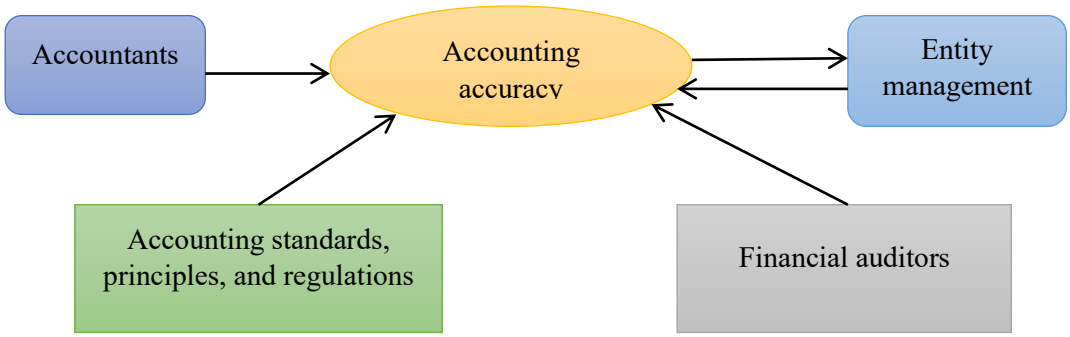


Figure 1. Factors influencing accounting accuracy

Source: author's own conception

Accountants, based on specific methods and procedures, provide financial and accounting reports to management. The accounting system allows information to be obtained on the financial position and performance of an entity. Compliance with specific rules and regulations ensures, to a large extent, accounting truthfulness because it allows the verification of the recording of economic operations in the accounts. Accounting rules, principles, and regulations form the conceptual basis of accounting and provide practical solutions for solving tasks. When preparing financial statements, accountants must apply all accounting principles, including the entity principle. According to this principle, which is based on economic, financial, and legal criteria, the accountant distinguishes between the economic entity and its owners based precisely on legal criteria, although this seems and is quite difficult. The methodology for presenting information in financial statements, as well as the accounting methodology, depend on the implementation of the principle of economic priority over legal priority. However, qualitative characteristics contribute significantly to ensuring accounting accuracy in an entity. Standardization plays an important role in ensuring accounting truth, as confidence in financial and accounting information can be ensured mainly through the application of rules issued by the competent institutions. Neither theoretically nor practically is the need for accounting standardization questioned; only the degree of standardization is debated. The discussion concerns the number of rules, as too many rules hinder the development of accounting, while on the other hand, giving too much leeway to accounting reasoning can have negative consequences. Standardization consists of fulfilling the following functions: it makes it possible to obtain financial and accounting information; it allows for the verification of financial and accounting information through internal and external control; it creates a climate of trust in the financial and accounting information presented by the entity; it ensures the arbitration of any

conflicts between the contracting parties; it allows for the comparison in time and space of the information contained in the financial statements prepared in accordance with those standards. In the view of some researchers, a set of normative acts forms accounting law because, they argue, the provisions included in those normative acts create unique requirements at the state level in this area. Financial auditing ensures the necessary confidence for users of the information contained in financial statements, and it is indisputable that, no matter how successful standardization may be, this is reflected in the audit. Auditing has emerged as a necessity for financial and accounting information to bridge the gap between providers (economic entities) and users. Independent professionals—auditors—provide confidence that accounting principles, rules, and regulations are being applied correctly. Thus, the accuracy of financial and accounting information is confirmed or refuted by auditors and expressed through the issuance of an opinion in the audit report. The entity's management is required to ensure compliance with rules, principles, and regulations, to ensure the organization and management of accounting, and to submit financial statements for verification by financial auditors, internal auditors, accountants, tax inspectors, management inspectors, and appraisers, as appropriate.

4.2. Assertions and reflections on confidence in accounting truth/accurancy

The key elements of ensuring confidence in the financial and accounting information presented in the annual financial statements of public interest entities and, at the same time, of consolidating accounting truth, consist of reflections and assertions according to Table 1.

Table 1. - Assertions vs. reflections on trust in accounting truth/accurancy

Assertions		**Reflections**
• The assertion regarding completeness refers to the fact that financial and accounting information must include all transactions and events that could significantly affect the financial position of the public interest entity. • The assertion regarding accuracy focuses on the fact that financial and accounting information must be correct and reflect the reality of the economic operations carried out during the financial year.		• Financial auditing is an essential process in confirming the accuracy and reliability of financial accounting information. • The standards and rules for reporting financial accounting information produced at the level of a public interest entity contribute directly to maintaining the quality and accuracy of that information. • Transparency and communication are also central elements of reflection, increasing confidence in the accounting truth promoted to

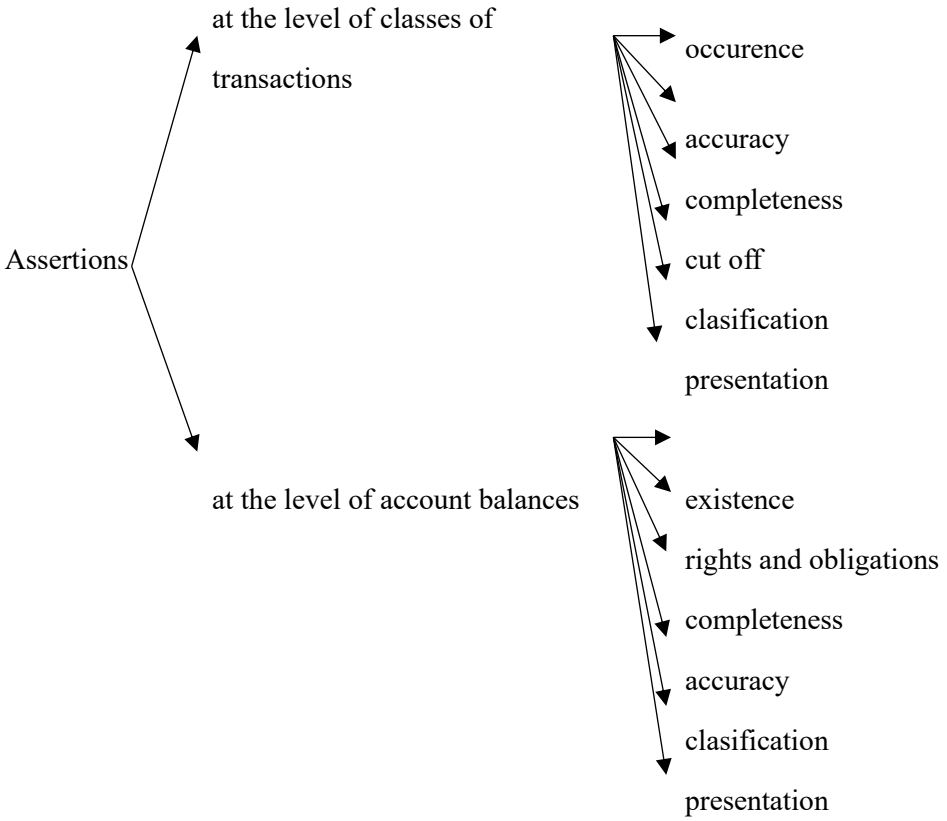
• The assertion regarding validity (timeliness) refers to all transactions and events that must be recorded in the accounting records of the public interest entity during the period in which they occurred, while complying with the applicable accounting principles and rules. • The fairness assertion focuses on the objective presentation of financial and accounting information, without distortion or subjectivity.	**VS.**	users of financial and accounting information. • Corporate governance should provide a solid framework comprising an active audit committee and a responsible board of directors that could strengthen confidence in the accounting truth promoted through the financial statements of public interest entities, which is not the case at national level.

Source: author's own conception

If we take a look at another approach, the set of assertions and reflections on accounting truth is considered to be interdependent, as follows: accuracy vs. integrity – requires that financial and accounting information be accurate and fairly reflect the transactions and economic operations of the public interest entity; relevance vs. materiality – requires that financial and accounting information be relevant on the one hand and have the capacity to influence managerial decisions on the other; completeness vs. exhaustiveness refers to the fact that financial statements must provide a complete picture of the public interest entity without material omissions; consistency vs. consistency attributes consistency over time and compliance with the applicable accounting framework to financial and accounting information; transparency vs. communication requires that financial and accounting information be subject to open communication so as to express its essentiality in constructing accounting truth; Supervision and regulation show the ongoing need for adequate monitoring and regulation of financial and accounting information in the application and compliance with accounting standards to avoid manipulation of such information according to various interests; Independent examination is the attribute of financial auditing that directly contributes to strengthening confidence in accounting accuracy by confirming or identifying deficiencies and risks associated with financial and accounting information. Governance responsibility for preparing and presenting the financial statements of public interest entities in accordance with accounting and ethical standards. Commitment to integrity unequivocally maintains confidence in accounting accuracy, with public interest entities required to demonstrate an ongoing commitment to integrity and ethics in all financial and accounting activities. dependence on financial auditing stems from the fact that financial auditing plays a decisive role in confirming the accuracy and credibility of financial and accounting information.

According to ISA 500 (IAASB - IFAC, 2018), assertions are statements contained in annual financial statements and are structured into three main categories, as follows (Table 2.):

Tabel 2. Assertions according to ISA 500



Source: author's own conception

An applied exposure regarding the assertions to be tested at public interest entities also focuses on the financial audit of fixed assets whose recognition was carried out in accordance with the provisions of M.F.P. Order no. 2844 of December 12, 2016, which specifies that fixed assets represent resources that will generate economic benefits in the future and are recorded in accordance with IFRS standards, including intangible and tangible fixed assets, assets in the process of procurement or execution, productive biological assets, rights to use leased assets, and financial fixed assets. The risk factors associated with tangible fixed assets arise from: technological advances in the sector of activity of the public interest entity under review, leading to the obsolescence of fixed assets; the closure of a sector of activity of the entity requires the valuation of fixed assets at net realizable value, if this is lower than the initial cost; estimating the economic life for depreciation purposes can be difficult, which can lead to overvaluation or undervaluation

of the value of fixed assets; the risk of holding blocked and unused fixed assets, generating uncertainty regarding their future use; fixed assets in progress that can be sold at significant amounts, but whose completion date is uncertain; capitalization of costs associated with assets produced in-house, with impediments in calculating the associated costs; movable fixed assets, which have high values and present significant risks of loss, theft, or damage. The completeness of tangible/intangible assets, for example, is tested by setting the objective of ensuring that all tangible and intangible assets have been included and presented in the financial statements. Thus, misstatement arises from: discrepancies between accounting records and operational records, which creates increased risk at the entity level due to the fact that it does not have an integrated record-keeping system, and the reconciliation between the two records, namely accounting and operational, is performed using outdated methods where human error is almost uncontrollable.

4.3. Possibilities for achieving accounting truth/accurancy

The writer Luigi Pirandello answered the question "Is there such a thing as accounting truth?" in his own style, namely, "To each his own truth." Given that for different social protagonists the truth can be presented in financial statements according to their interests, we consider that the truth for producers of financial and accounting information is a balance between compliance with fundamental rules and principles and sincerity, and for users of information it is the result of a compromise between requirements and expectations. In order to enlighten ourselves regarding the "Table of Contents of Accounting Freedoms," we present the following classification for the sake of accounting truth:

- permitted accounting policies – which are represented by the options for applying basic treatment and alternative treatments;
- accounting assessment – which involves possibilities for preferential application, as follows:
  - application of the asset impairment test;
  - application of the revaluation of fixed assets;
  - application of changes in inventory valuation methods;
  - application of subjective valuation of intangible assets and financial securities;
  - application of changes in the rate of depreciation;
  - applying flexible accounting policies with regard to the creation of provisions;
  - applying internal prices for the disposal of assets and prices for disposal between subsidiaries of the same group;
- postponing actual transactions resulting in the manipulation of accounts;
- recording large differences between the purchase price and the book value on the basis of the undervaluation of the acquired asset and charging the differences to reserves;

- applying "lease-back" operations by selling an asset and immediately leasing it back from the purchasing company. This improves cash flow, reduces the debt ratio, and increases profits;
- reducing losses recorded on receivables by taking out insurance, which leads to an improvement in the result equal to the difference between the insurance premium paid and the amount of the impairment of the receivable.
- operating a "de facto debt write-off" consisting of transferring assets to another economic entity, together with debt management.
- Prudent and aggressive accounting treatments with regard to income and expenses, thus creating a performance calculated according to interest/desire;
- Accounting treatments for increases and decreases in value due to uncertainty and risk, aggressive and conservative or through hedge accounting;
- accounting options and freedoms regarding capital maintenance through:
  - maintaining the nominal value of financial capital by recovering historical cost,
  - valuation bases,
  - time value of money;
- accounting freedoms in the delicate relationship between taxation and accounting, as follows:
  - commercial accounting versus tax accounting;
  - financial accounting versus business accounting;
  - management accounting versus cost accounting;
- multiplication and diversification of accounting freedoms regarding the presentation of information, analysis, and interpretation of general-purpose financial statements.
- analysis of forecast and interim information.

Freedom and compliance represent an equation of relevance and credibility in financial statements. Relevance is characterized by the provision of predictive and retrospective knowledge necessary for making effective economic decisions regarding the performance and financial position of an economic entity, while credibility is characterized by obtaining financial information that is free from material misstatement, unbiased, and in which users can have confidence that it represents a true and fair view as reasonably expected by them. When relevance and credibility exist, the following question stubbornly arises: is accounting capable of conveying truth and an objective message? To answer this question, the literature reveals several assessments, including the following: French professor A. Cibert states that *there are as many truths as there are recipients of information and that, to the extent that it excludes quality, the reductive effect of each measurement is inevitable, while P. Lasseque, B. Colasse, and D. Boussard admit that the truth told by accounting is nothing more than a filter that allows for the understanding of a reality. However, due to its internal consistency, which gives it both strength and weakness, accounting allows us to arrive at a formal truth based on a few postulates, conventions, norms, and classification rules*. From another perspective, the equation of freedom and conformity in

standardized/regulated accounting, with reference to IAS 1, Presentation of Financial Statements, can be expressed as shown in Figure 2:

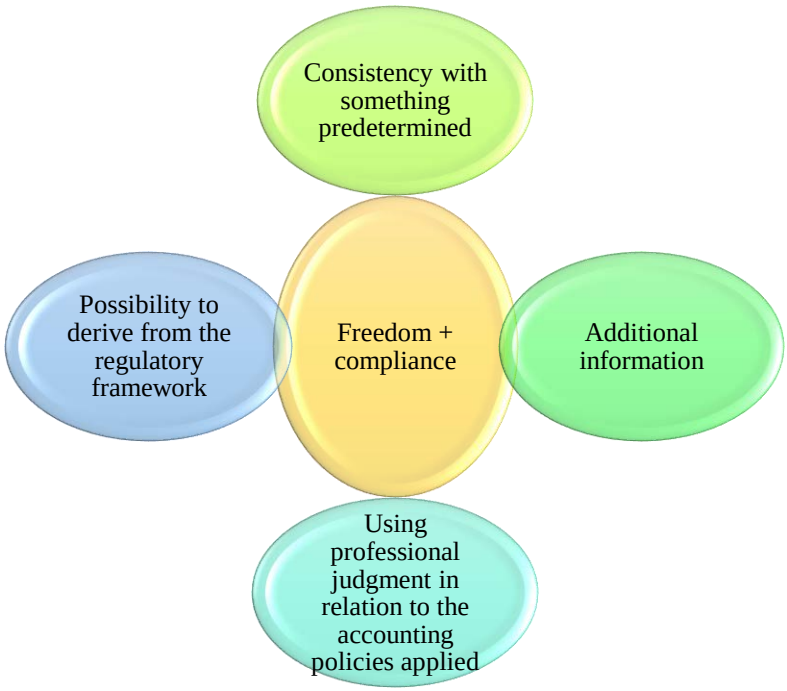


Figura 2. Freedom and compliance equation
Source: author's conception

It should be noted that economic entities that prepare financial statements in accordance with IFRS must submit a statement in the explanatory notes regarding this compliance and, on the other hand, if they issue this statement, they must comply with all IFRS provisions. Practice has shown that in almost all cases, entities applying IFRSs present their financial statements fairly. However, an economic entity cannot justify the application of inappropriate accounting policies through notes or explanatory materials. However, in very rare cases, when the entity considers that compliance with a provision of an IFRS would be so misleading that it would conflict with the objective of financial statements set out in the Framework, it may depart from that requirement if the relevant regulatory framework does not otherwise prohibit or require such a departure (interpretation from IAS 1 Presentation of Financial Statements). The choice of accounting methods and freedom in formulating accounting policies specific to the entity's business, although viewed positively by practitioners and managers, can be a source of controversy in determining accounting truth because it has been found that the use of different methods leads to different results. For this case, the IASB recognized that to ensure harmonization, it is necessary to reduce the

possibility of using permitted alternative treatments. In exercising professional judgment, accountants and managers should consider applying the following sources:
1. guidance in standards and interpretations that deal with related or similar issues;
2. definitions, recognition criteria, and measurement concepts in the Framework for Assets, Liabilities, and Financial Statements.
In exercising the judgment presented, accountants may consider accepted practices in the field and the latest standards issued by other standard-setting bodies that use a similar conceptual framework, to the extent that they do not conflict with specific standards. We note that entities must select and apply accounting policies consistently. At the same time, we recognize that accountability and transparency are essential where freedom and compliance apply in the selection and application of accounting policies. Professional judgment is an integral part of the preparation of financial statements. All accounting professionals, including auditors, are required to use professional judgment in their work. The rules that can be derived from the need for uniformity and certainty in financial statements are:
1. rules established within the economic entity that lead to the uniform application of specific accounting policies;
2. rules established by an auditor/audit firm specific to the country in which they are applied;
3. rules established by governments and regulatory bodies with a view to standardizing them globally.
Accountants are always in the middle of this triangle of rules; in practice, they are the ones who apply their own reasoning, evaluate the reasoning of managers, and will be judged by information users (investors, the public, control bodies). To ensure uniform application of standards, professional accountants take on the challenge and implementation procedures. Accounting specialists do not have an easy life with the rules and will have to work with principles. It should be noted that the I.A.S.B. is the body that sets standards in an appropriate manner, and this is done on the basis of professional judgment. However, we believe that the attempt to classify accounting into rule-based accounting (regulations and norms) and principle-based accounting is unfounded. Opposing these two types of accounting means denying the formalism of the accounting information system. Accounting must be both constructive and normative, and if we doubt it, the only solution left is to switch from accrual accounting to cash accounting.

5. From accounting accuracy to the quality of financial accounting information between uncertainty and ambiguity.

The evolution of the quality of Romanian financial and accounting information can be analysed in correlation with the national historical context and developments in the field of accounting at the international level. On the one hand, economic relations within entities have become increasingly complex in recent years, and on the other hand, international

openness has multiplied the number of interactions between different economic entities. The paradigm regarding the global worldview has brought about changes in the political, economic and cultural environment and has accelerated the phenomenon of globalization and computerization in recent years, which has led to substantial changes in the need to obtain high-quality financial and accounting information without ambiguity and uncertainty. In this sense, the transparency of financial information and unrestricted access to reliable and timely information is essential for making decisions in conditions of performance within the environment in which an entity operates. In other words, from an economic point of view, transparency is a recognised attribute regarding the availability of relevant and reliable financial and accounting information on financial position, performance, investment opportunities and governance. The information policy is inseparable from the entity's overall communication policy and the need to convey clear, reliable, and concise information is an essential requirement of management policy.
The quality of financial and accounting information is influenced by the following factors (Figure 3.):

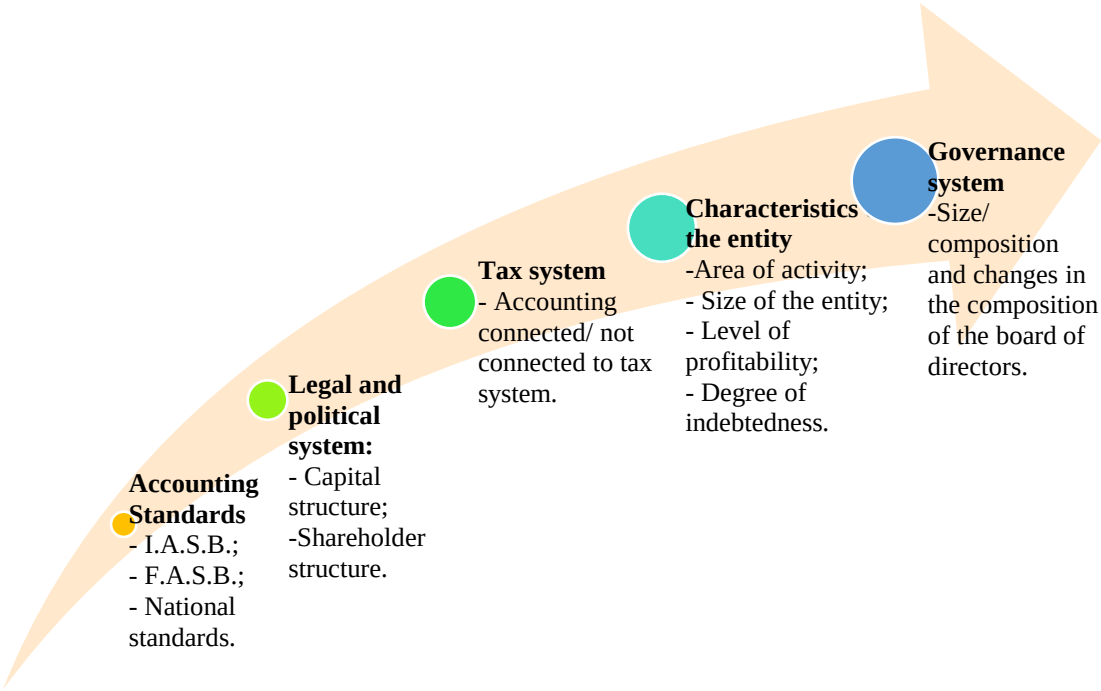


Figure 3. Factors that influence the quality of financial and accounting information

Source: author's own work based on Soderstrom and Sun, 2007 p. 688 [3]; Dechow, Ge and Schrand 2010 [4]

The preparation and presentation of an entity's financial statements in accordance with IFRS is governed by accounting rules and principles designed primarily to reduce the uncertainty affecting the measurement of income and financial conditions. For this reason, financial and accounting managers may choose the most appropriate methods for accounting for transactions according to the specific nature of the entity. This option allows accountants to create discretionary space to model financial statements without violating accounting rules. Being subordinate to the objectives of financial communication and managerial behaviour, these choices characterise the entity's accounting policy and, on the other hand, depending on their nature, mandatory or voluntary, this information is used in the communication process as necessary. While mandatory information must strictly comply with presentation rules and be verified by auditors, voluntary information enjoys a greater degree of freedom. Since these two categories of information do not correspond to the same needs, we can question the quality of periodic financial publications in managing accounting results and the role of the level of disclosure. Thus, some authors appreciate that "The issue of financial reporting quality has attracted the interest of several researchers whose opinions converge towards the idea that it can be influenced both by factors related to the company's internal environment, the corporate governance system, the activity of auditors, as well as macroeconomic factors, such as the legal and political system of a country or community or certain accounting/tax policies" (Ciocan C. Carp M. Georgescu I.) [5].

6. Financial and accounting information between a true and fair view and validation through financial audit.

The most important quality that financial and accounting information must have, is a true and fair view, which is in fact the result it must achieve. According to Article 23 of the implementing regulation of Accounting Law No. 82 of December 24, 1991, financial statements must present a true, clear, and complete picture of the economic reality of an entity.

6.1. Fair presentation - fundamental objective of accounting: conceptual elements, interpretations

The presentation of financial statements in accordance with the "fair presentation" principle is imperative; it is more than a guiding principle, and all accounting rules and principles shall be subordinate to this meta-principle, although it enjoys a certain degree of ambiguity. In Romania, in theory, this concept has been perceived as ambiguous due to subjective considerations related to the technical accounting mentality, but also due to some objective considerations related to the regulation of accounting law. Thus, the ambiguity denounced by the concept of a true and fair view stems from a double subjective consideration, namely: the view is provided by its producers and is intended for information users, who are most often different persons and faithfulness implies the provision of complete information, but without being limited to this criterion of exhaustiveness (which can be considered an

element of the principle of sincerity), clear, intelligible, easy to use (without losing relevance). The faithfulness of information also implies that its producers take into account external recipients and are objective. A faithful image can be represented by the phrase "an image that can be trusted," because the idea has been established that there can be several faithful images without representing an exact copy of reality. In continental Europe, accounting rules did not refer to "faithfulness" or "loyalty" in terms of accounting information because, based on a practice and doctrine that reflected economic reality accurately, accounting was considered a tool of precision, subject to proof of falsehood, and the notion of "fidelity" brought with it a shadow of uncertainty. The definition of "true and fair view" has never been given in continental accounting law. The concept of the objective of a true and fair view of financial statements was borrowed from the British, through the Fourth Directive of July 25, 1978. Although four decades have passed since the true and fair view was proposed through the Fourth Directive, there is still no universally accepted definition to this day. Moreover, each member state of the European Union, based on the prescriptive nature of European Directives, has adopted and adapted this concept in national accounting regulations, taking into account its own needs, thus managing to impose a concept foreign to its own culture. In the specialized literature, we found the existence of more or less conflicting situations between the objective of a true and fair view and certain accounting principles, the most significant of which are those concerning the effect of pessimism associated with the principle of prudence and the controversies regarding the effect of valuing items in financial statements based on historical cost to the detriment of current values. The late Professor Niculae Feleagă argued that prudence is a complement to a true and fair view and implies not presenting an overly favorable view, nor ignoring events or facts that could have an impact on future financial situations. This reference is particularly important because it allows us to avoid deviating from the principle of prudence, namely: it is not a question of the producer of accounting information behaving "prudently" in order to protect himself, but rather of protecting the user of the information, in the sense that the latter should not base his analyses on an overvalued patrimony.

6.2. Fair presentation – subject of reporting in financial auditing

Fair presentation is a qualitative criterion of standardization, being both a flexible concept, when it represents the starting point for possible developments in regulation, and a stable concept, when it supports accounting regulation. Fair representation is the condition established for information to be credible. Financial statements are prepared in accordance with the requirements of the general accounting framework, and the accountant must ensure that the financial statements present a fair view of the entity. According to IAS 1, financial statements must present a true and fair view of the financial position and results, thus providing information to all categories of users. The concept of a true and fair view has been incorporated into European regulations through Directive IV, which sets out the requirements for the preparation of financial statements. In order to achieve a true and fair

view of the financial statements, the Directive allowed for the disclosure of information in addition to that required by the regulations, as well as the inclusion of exemptions, provided that these are presented in the notes and their impact on the financial statements is disclosed. The standardization of the concept of a true and fair view was achieved with the harmonization of International Accounting Standards with European Directives. Following the French model, Romania adopted the faithful image by adopting the principles of sincerity and compliance with the rules. The fundamental objective of the accounting informational system is the presentation of the faithful image of an entity's patrimony. Anglo-Saxon accounting uses the notion of the principle of sincerity, while continental accounting uses the notion of faithful image, which can be represented by the formula: Faithful image = regularity + sincerity. The difference between these principles is similar to that between the spirit and the letter of the law. Sincerity rather addresses complex operations that also involve professional judgment, therefore reflecting a degree of subjectivism and cannot be regulated in detail, while regularity addresses simple, repetitive operations that can be regulated and formalized in the smallest details. "Although today the faithful image seems to be a common denominator of all accounting systems in the European Union (and not only), the significance of the concept, but especially the way of application, still creates significant differences. Nevertheless, one can speak about the existence of a common core of the concept throughout the entire European Union." (Liliana Feleagă, Niculae Feleagă, 2007, [6]). There are many controversies created around the faithful image; the Anglo-Saxon world considers that it is an evolutionary process that cannot be "frozen by the will of the legislator or by the letter of a standard. In this context, the legal norm, a product of the faithful image, becomes a rule of life, and not a dead principle, without spirit." (Liliana Feleagă, Niculae Feleagă, 2007, [6]).

In a comparative table (Table 3), the fair presentation, according to IAS 1, the General Framework, and Directive IV, is as follows:

Table 3. The fair presentation, according to IAS 1, the General Framework, and Directive IV

I.A.S. 1	General Framework	Directive IV
1. The information presented must be reliable, relevant, comparable, and understandable. 2. It requires the accurate representation of transactions in accordance with the provisions set out in the general framework.	1. It is a qualitative characteristic of financial information. 2. The application of professional	Assets, liabilities, financial position, profit or loss must be accurately reflected in the accounts.

3. Complying with IAS requirements ensures that a true and fair view is always achieved, as obtaining a fair presentation requires: - identifying and applying an accounting policy that ensures compliance with accounting standards; - the form of presentation of all accounting information should ensure credibility, relevance, comparability, and understandability; - when the requirements of the standards are insufficient, additional information should be provided to clarify the impact of those transactions on the financial position and results.	judgment needs to ensure a true and fair view in the presentation of financial statements.	The balance sheet, profit and loss account, and annual report forms and the minimum content of the notes are mandatorily provided.

Source: author's own work

In order to ensure a justified, independent and competent opinion on the faithful image reflected in the financial statements, statutory audit must ensure the observance of the following criteria: 1. the criterion of correct presentation and recording in accounting based on the use of accounts; 2. the criterion of the reality of the recordings. In this case, the auditor must verify whether all transaction records are verifiable and correct and whether all transactions belong to the entity. In this case, the expression, in equivalent terms, that auditors insert in audit reports when expressing an opinion is that the financial statements "*present, in all significant aspects*" or "*the financial statements provide a faithful image.*"

6.3. Does the faithful image reflect the truth in accounting?

The recommendations of the regulatory body of the American accounting profession promote the idea of the credibility of financial statements through the faithful presentation of financial–accounting information, in accordance with Generally Accepted Accounting Principles (GAAP – Figure 4), the essential framework for establishing the rules and guidelines in the preparation of financial statements in the United States of America. These two definitions are often criticized because the attainment of accounting truth cannot be linked to compliance with rules or generally accepted principles, that is, to a framework resulting from standardization, but rather to human will at a certain moment.

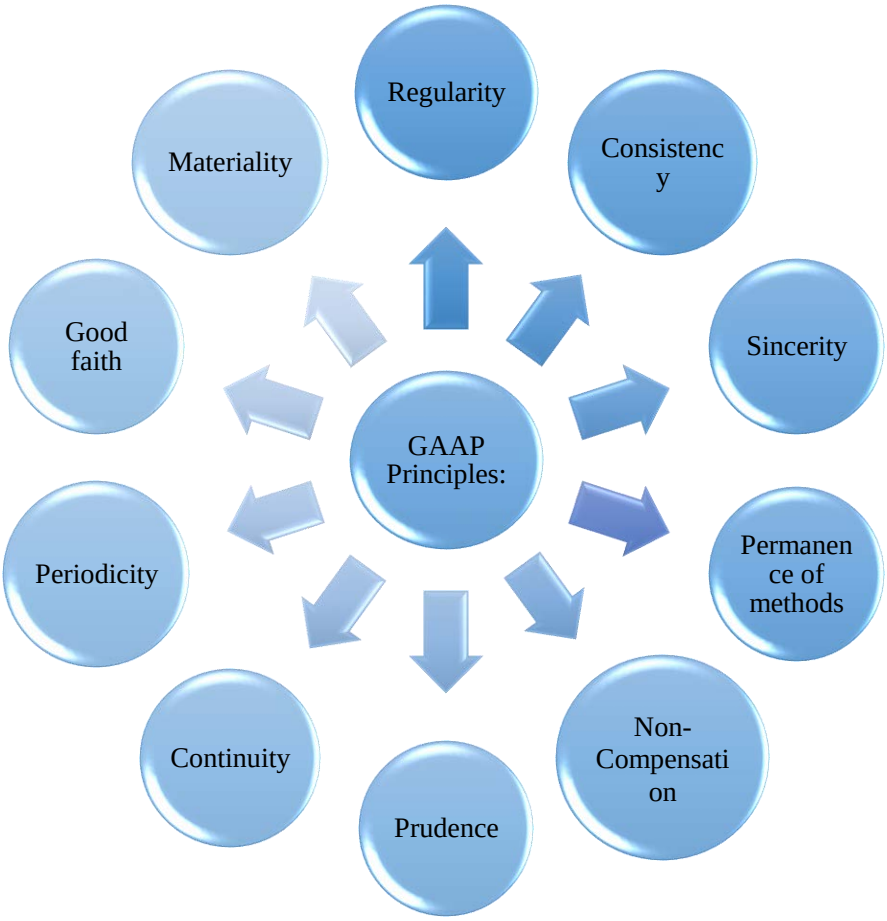


Figure 4. – The GAAP principles
Source: author's own work based on < https://www.accounting.com/resources/gaap/ >

Another approach to the faithful image, which in our opinion responds to the requirements of scientific truth, is characterized by completeness, being identified in the Anglo-Saxon treatment according to which sincerity and fidelity are the pillar components of fidelity. Sincerity is considered only one of the stages in the search for an authentic representation of the public interest entity, thus satisfying the requirements of fidelity in the conceptual sense, since reality may be insufficient when encountered in an unfavorable context. Thus, fidelity is not limited only to the description of reality, but also includes its sincere presentation, especially since, in Anglo-Saxon accounting, the professional judgment of the accountant is prioritized as an element capable of building credibility in accounting, the accountant being endowed with sincerity and especially with fidelity, but not least with professionalism. Therefore, we can conclude that in the Anglo-Saxon conception, a faithful image must be and is considered to be the truth in the field of accounting. The specialized literature emphasizes that "standardization contributes essentially to the presentation of

accounting truth, constrains the behavior of the management of public interest entities, and ensures the comparability of data in space and time. However, standardization cannot be perfect, and this is a fact that the management of entities may exploit in order to manipulate the information used in the preparation of financial reporting" (Țurcanu & Golocialova, 2016) [7].

7. From accounting truth and faithful image to the role and relevance of financial audit in the economic environment

7.1. Financial audit – a relevant factor in confirming accounting truth and validating the faithful image in the accounting of the public interest entity

Major financial scandals have, for the most part, originated in a distorted representation of reality through the generalization of error and fraud, or through their concealment. As long as the faithful image is not based on the principles of objectivity, correctness and transparency, the accounting profession will suffer, and the social role of accounting will not serve common interests, but compromise in favor of some. If financial–accounting information is not the result of ethical conduct and compliance with standards, the truth is manipulated, inducing a false perception among the users of that information and especially among investors. Accounting truth constitutes the watchword of financial audit and corporate management, the latter obviously being the most interested in its manifestation considering that corporate governance applied at the level of a public interest entity is focused on increasing transparency and "improving the quality of the information presented publicly by them, through the implementation of corporate governance principles for public enterprises," as specified in art. 1, para. (1) of Emergency Ordinance no. 109 of 30 November 2011. Specialized literature considers accounting to function as both an information system and a control instrument at the same time, fulfilling its functions according to the requirements of the Accounting Law and the applicable regulations in force. Thus, through the use of double-entry recording and the system of accounting accounts, the activity of the public interest entity can be modeled, and the final result is materialized in the set of financial statements dedicated to satisfying the requirements of all users. Standardization has a major role in promoting accounting truth, influencing the behavior of those responsible for governance at the entity level, while also ensuring the comparability of data in time and space. Nevertheless, we could say that standardization cannot be perfect, and this can be exploited by those responsible for governance in order to manipulate financial–accounting information.

According to European and national regulations, the financial–accounting information processed through the accounting system of the public interest entity and presented in its financial statements is characterized by credibility if it is verified by financial auditors, thus increasing its value for the direct users of this information, and after auditors confirm the correctness of the financial–accounting information, it can be concluded that it may be used for making correct decisions or, in other words, it can certify accounting truth.

Presenting the accounting reality also involves disclosing its assurance factors, as can be seen in Figure 5.

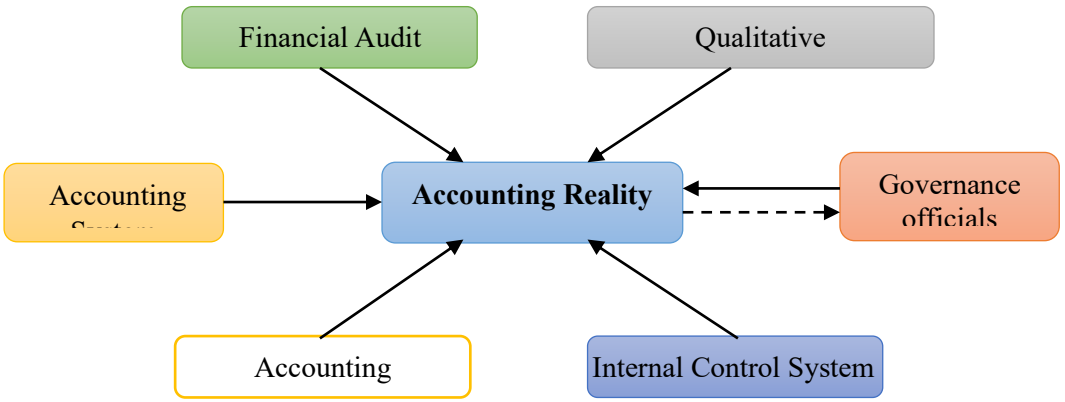


Figure 5. – Accounting reality factors
Source: author's conception

A distinctive feature of accounting is that in this field the human being is both object and subject, accounting truth being a concept that remains valid as long as the conditions that validated it remain the same, while also showing that in accounting there is not a single representation of the same reality. Thus, in the context of the present scientific approach, accounting standardization represents a pillar factor of accounting, fulfilling a series of functions, such as: "contributes to obtaining financial information; creates a climate of trust in the information presented by the entity; ensures the verification of financial information, both through internal and external control; allows the arbitration of possible conflicts between the contracting parties; makes possible the comparison in space and time of the data presented in the financial statements" (Țurcanu & Golocialova, 2016) [7].

In our opinion, due to its nature, truth represents the abstract interpretation of certain phenomena, processes and concrete realities, a fact that determines the reality captured by accounting as a form of truth through which the public interest entity exposes its own identity, considering both its present and future interests. Although audit and accounting aim to identify and validate an accounting truth, it is the result of the human cognitive process and cannot be considered absolute. Thus, we consider that accounting truth, regardless of its level of fidelity, represents the consequence of an investigation which, to a certain extent, always brings to attention an element specific to subjectivism.

7.2. The role and relevance of financial audit in the public entity: the credibility of financial–accounting information and the degree of trust for users

Financial audit plays an *essential role in the economic environment by providing credibility to financial–accounting information and strengthening the degree of trust for the users of this information*. At the same time, the relevance of financial audit in Romania is of particular interest for several reasons, among which we mention: compliance with specific legal regulations: financial audit is mandatory for certain entities in accordance with Romanian legislation, as well as with the regulations of the European Union. It ensures compliance with accounting standards and other legal requirements regarding the preparation and presentation of financial statements; protection of stakeholders: financial audit is essential for protecting the interests of stakeholders, such as investors, creditors and other entities, ensuring that the financial information provided is correct, complete and credible, a favorable context for increasing trust in the business environment in Romania and at the same time for attracting investments; supporting the decision-making process: reliable and verifiable financial information guaranteed by financial audit is vital for the decision-making process of corporate management, investors and other stakeholders. This information contributes to the evaluation of the financial performance of a public interest entity, as well as to making informed decisions regarding investments, financing and other aspects of the business; detection and prevention of fraud and errors: financial audit plays an important role in detecting and preventing fraud, as well as errors in the financial statements of public interest entities, for which purpose financial auditors perform detailed audit procedures to identify possible anomalies and deviations from accounting practices, but also to report these issues in a timely manner; promoting transparency and good corporate governance practices: financial audit contributes to promoting transparency and good corporate governance practices within public interest entities in Romania. It ensures that internal control and reporting procedures are adequate and efficient, which increases the confidence of users of financial information.

Therefore, in our opinion, the relevance of financial audit in Romania is vital for ensuring legal compliance, protecting the interests of stakeholders, supporting the decision-making process, detecting and preventing fraud, as well as promoting transparency and good corporate governance practices in the Romanian economic environment.

The main elements of the role and importance of auditing are shown in Figure 6.

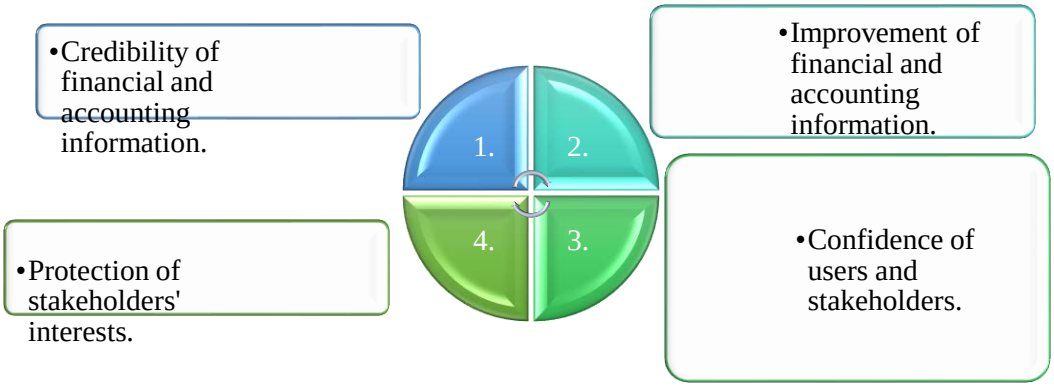


Figure 6. The main elements of the role and importance of auditing
Source: author's conception

The credibility of financial–accounting information: financial audit provides an independent and objective evaluation of the financial statements of a public interest entity, thus adding credibility to the financial–accounting information provided by that entity, confirming that it is correct, complete and compliant with the applicable accounting standards. Improvement of the quality of financial–accounting information: through the careful examination of transactions, accounts and other financial aspects, financial auditors contribute to the identification and correction of errors, fraud and other non-compliances, in this context enhancing the improvement of the quality of the financial–accounting information provided, while also increasing its usefulness in improving managerial decisions of an economic nature. Users' confidence: the independent opinion issued by financial auditors provides the users of financial–accounting information with an increased degree of confidence in its accuracy and integrity. This is essential for investors, creditors, governments, regulators and other interested parties who rely on financial–accounting information to support their decisions and to evaluate the financial performance of an entity. Protection of stakeholders: financial audit contributes to protecting the interests of stakeholders, including investors and creditors, by identifying and reporting any significant problems or irregularities in the financial statements of a public interest entity, creating a favorable context for increasing the transparency and responsibility of those entities, while also protecting the financial interests of stakeholders.

Financial audit is essential in the economic environment to ensure credibility, quality and trust in the financial information provided by public interest entities. By providing an independent and objective opinion on financial statements, financial audit contributes to strengthening users' confidence and protecting their interests in improving economic decisions. Financial audit is designed to provide independent assurance that financial statements are presented appropriately in accordance with the applicable accounting model and that the information provided is credible and relevant for the users of this information.

Therefore, the audit engagement plays a major role in promoting trust and transparency in the economic and financial environment.

7.3. The responsibility of the financial auditor and the commitment to the imperative interest of strengthening trust in the quality of financial–accounting information

The financial auditor is required to comply with ethical requirements, including those related to independence, within audit engagements carried out on the financial statements of the public interest entity, while also being subject to the fundamental principles promoted by IFAC, namely: integrity, objectivity, professional competence, confidentiality and, last but not least, professional behavior. At the same time, the financial auditor must approach the audit with an adequate level of professional skepticism, being aware of the possibility of material misstatement of the financial statements, paying particular attention to aspects such as: audit evidence that contradicts other audit evidence obtained; information that raises questions regarding the reliability of documents; circumstances that indicate the need for additional audit procedures beyond those required by ISA standards. Maintaining an adequate level of skepticism throughout the audit is essential in order to minimize the risk of overlooking unusual circumstances, excessive generalization in drawing conclusions from audit observations and the use of inappropriate assumptions in determining the nature, timing and extent of audit procedures, as well as in evaluating their results. Thus, professional skepticism is essential for critically evaluating audit evidence, including questioning contradictory audit evidence and assessing its adequacy. Professional judgment represents the cornerstone in conducting an appropriate audit and is essential especially in the decision-making process regarding certain aspects, among which the most relevant are: establishing the materiality threshold and managing audit risk; defining the nature, timing and extent of the audit procedures used; evaluating the extent to which adequate and sufficient audit evidence has been obtained; analyzing the correctness of the application by management of the general financial reporting framework; formulating conclusions based on the audit evidence gathered. Thus, in order to provide reasonable assurance, the auditor must collect adequate and sufficient audit evidence capable of reducing audit risk to an acceptable level, thus allowing the formulation of responsible conclusions on the basis of which to express an opinion. The financial auditor must comply with all relevant ISAs which, taken together, establish norms for the auditor's activity in fulfilling objectives, including general responsibilities, without neglecting legal requirements or national regulations, noting that ISAs do not substitute the laws or regulations governing the conduct of an audit. The financial auditor has the responsibility to express an opinion on the financial statements, being oriented toward verifying compliance with the conceptual framework of accounting, compliance with internal procedures established by those responsible for the governance of the public interest entity, but also toward verifying and certifying the fact that the financial statements faithfully, clearly and completely reflect the image of the entire financial year. Thus, *"the level of assurance of the auditor in an audit engagement must be*

very high but not absolute, being based on the evaluation of the audit evidence collected as a result of the procedures applied", following at least two essential aspects, namely: "*1. the validity and correct application of the internal procedures approved by the management of the entity regarding the way internal control and internal audit are carried out, where applicable; 2. the faithful, sincere, clear and complete image of the transactions and other events that materialize in the assets, liabilities and equity of the entity at the reporting date, with the fulfillment of the recognition criteria*." (Munteanu & Duță & Soare, 2020) [8].

8. Conclusions.

Due to its nature, truth represents the abstract interpretation of certain phenomena, processes and concrete realities, a fact that determines the reality captured by accounting as a form of truth through which the public interest entity exposes its own identity, considering both its present and future interests. Although audit and accounting aim to identify and validate an accounting truth, it is the result of the human cognitive process and cannot be considered absolute. Thus, we consider that accounting truth, regardless of its level of fidelity, represents the consequence of an investigation which, to a certain extent, always brings to attention an element specific to subjectivism. In the current economic context, financial–accounting information plays an essential role, being situated between two fundamental concepts: the faithful image and validation through financial audit. The concept of faithful image implies the correct, clear and complete presentation of the economic reality of a public interest entity, in accordance with accounting rules and principles. On the other hand, financial audit represents the process of examining and evaluating financial statements in order to confirm whether they faithfully reflect the financial image of the entity and comply with accounting standards and legal regulations. Thus, financial–accounting information finds its balance between these two concepts, ensuring transparency, trust and compliance with standards in the field. The increase in rigor in regulating financial audit activity has led to a visible improvement in the quality of financial–accounting information made available to users, thus fulfilling the main objective of financial audit. Thus, financial audit actively participates in improving financial–accounting information in the sense of enhancing its value both from the perspective of users and in terms of satisfying the public interest. The certification of accounting truth is particularly important, but ensuring it does not fall exclusively within absolute assurance, especially because it is mainly achieved based on qualitative criteria rather than quantitative ones, which is why we can state that the assurance provided by financial audit cannot be considered absolute. The financial auditor assesses that the financial statements of the reporting public interest entity express a faithful image exclusively through the compliance of financial–accounting information with a regulatory framework, while the professional competence of the financial auditor and the auditor's professional ethics in the explicit conduct of the audit engagement focus on expressing reasonable assurance regarding

accounting truth in full interdependence with the application of the principles of ethics, independence and objectivity.

Inaccurate information included in financial statements is considered significant when the combination of error and undetected fraud could change or influence the good-faith decision-maker who is a user of that information. Since quantifying the materiality threshold becomes a difficult task, auditors are responsible for obtaining reasonable assurance regarding compliance with this threshold, therefore imposing an obligation on the auditor to discover all insignificant errors and frauds would be unproductive. Within the audit strategy and planning, allocating time for discovering unintentional errors made by managers and employees is an important aspect. Auditors encounter a variety of misstatements that arise from actions such as calculation errors, omissions, misunderstanding or misinterpretation of accounting policies, or inaccurate recording and description of transactions. ISA 240 (IAASB - IFAC, 2018) precisely establishes the responsibility of the financial auditor in relation to the execution of the audit of financial statements in accordance with the ISAs in order to obtain reasonable assurance that they do not contain material misstatements resulting from errors or fraud. The uncontrollable risk that some material misstatements may not be detected even under conditions of properly designed planning represents an inherent limitation, and according to ISA 200 (IAASB - IFAC, 2018) the effects of inherent limitations are visibly manifested in situations of misstatements generated by the occurrence of fraud. Thus, the risk of material misstatement represents the risk manifested in the financial statements in the sense of distortion before the performance of the financial audit and may materialize in two directions, as follows: 1. at the level of the financial statements as a whole, referring to risks of material misstatement which, in turn, are strictly related to the financial statements as a whole and have a possible effect on assertions; 2. at the level of assertions (classes of transactions, account balances, presentations), these being evaluated in order to determine the nature, timing and extent of additional audit procedures necessary to obtain sufficient and appropriate audit evidence. It is entirely natural that both the responsibility and liability of the auditor should be proportional in the circumstances of maintaining a rational balance of responsibility, so that the auditor may achieve the main purpose, namely: providing certainty regarding the quality of the services offered by the auditor, without generating negative side effects through the creation of excessive pressure whose outcome may lead to the failure to achieve the intended objective. Moreover, specialized literature, but especially empirical studies, have demonstrated that excessive exposure of the auditor to liability has harmful consequences for efficiency and for the freedom of rational thinking. This may lead either to the commission of accidental errors or to the defective performance of an audit engagement. Due to their responsibility, auditors are inclined to reduce their potential liability in the case of a defective audit that does not comply with the necessary standards and norms.

References

[1] Gray, S.J., Coenenberg, A.G. ,Gordon, P.D. (1993), International group accounting: Issues in European Harmonization, London: Routlege.

[2] Colasse, B. (2007), The French notion of the image fidele: the power of words, European Accounting Review, vol. 6, nr. 4, pp. 681-691, DOI: http://dx.doi.org/10.1080/09638189700000009.

[3] Soderstrom N., Sun K.J, (2007), IFRS Adoption and Accounting Quality: A Review, European Accounting Review, vol. 16, issue 4.

[4] Dechow P., Ge W., Schrand C., (2010), Understanding earnings quality: A review of the proxies, their determinants and their consequences, Journal of Accounting and Economics, Volume 50, Issues 2–3.

[5] Ciocan C., Carp M. Georgescu I. Determinants of financial reporting quality: empirical evidence for Romania, Financial Audit Magazine, XIX, Nr. 2(162)/2021, 203-222 ISSN: 1583-5812; ISSN on-line: 1844-8801.

[6] Feleagă L., Feleagă N., (2007), Financial accounting: a European and international approach, volumul I, Economic Publishing House, Bucharest;

[7] Țurcanu V., Golocialova I. (2016), Accounting accuracy and its assurance at entities in the Republic of Moldova, Financial Audit, XIV, nr. 7(139)/2016, 714-726, ISSN: 1583-5812.

[8] Munteanu V., Duță F., Soare J., (2020), Financial Auditing, Theoretical and Practical Approach, University Publishing House, Bucharest.

Bibliography

Colasse, B. (2009), Fundamentals of Accounting (translated from French by N. Tabără), Iași: TipoMoldova Publishing House.

Magdaș, N., (2018), Auditor's Liability and Methods for its Limitation, Financial Audit Magazine, vol. XVI, no. 2(150)/2018, pp. 261-269, DOI: 10.20869/AUDITF/2018/150/011.

Directive 2013/34/EU of the European Parliament and of the Council of 26 June 2013 on the annual financial statements, consolidated financial statements and related reports of certain types of undertakings, amending Directive 2006/43/EC of the European Parliament and of the Council and repealing Council Directives 78/660/EEC and 83/349/EEC, OJEU L 182/19 of 29.06.2013.

Accounting Law No. 82 of December 24, 1991 (**republished**), issued by the Romanian Parliament, published in the Official Gazette No. 454 of June 18, 2008

International Financial Reporting Standards (IFRS), 2017, CECCAR Publishing House.

Order No. 1802 of December 29, 2014 - Part I for the approval of Accounting Regulations on individual annual financial statements and consolidated annual financial statements, issued by the Ministry of Public Finance, published in the Official Gazette No. 963 of December 30, 2014.

Emergency Ordinance No. 75 of June 1, 1999 (republished) on financial audit activity, issued by the Government, published in the Official Gazette No. 598 of August 22, 2003.

Law No. 162 of July 6, 2017, on the statutory audit of annual financial statements and consolidated financial statements and amending certain normative acts, published in the Official Gazette No. 548 of July 12, 2017.

Manual of International Standards on Quality Control, Auditing, Review, Other Assurance and Related Services, 2020 Edition, Volume I, International Federation of Accountants.

Manual of International Standards on Quality Control, Auditing, Review, Other Assurance and Related Services, 2020 Edition, Volume II, International Federation of Accountants.

Supplement to the Handbook of International Standards on Quality Control, Auditing, Review, Other Assurance and Related Services, 2020 Edition, Volume III, International Federation of Accountants.

IAASB, 2015a. International Standard on Auditing (ISA) 701 Communicating Key Audit Matters in the Independent Auditor's Report. [Interactiv] Available at: https://www.iaasb.org/publications/ internationalstandard-auditing-isa-701-newcommunicating-keyaudit-matters-independentauditors-4.

JOURNAL OF INFORMATION SYSTEMS & OPERATIONS MANAGEMENT

VOL. 20 NO. 1 / 2026

ROMANIAN-AMERICAN UNIVERSITY

ISSN: 1843-4711